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نموذج رقم (١٨)
اقرار والتزام بالمعايير الأخلاقية والأمانة العلمية
وقوانين الجامعة الأردنية وأنظمتها وتعليماتها
لطلبة الماجستير

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تخصص: الهندسة الصناعية الكليـــــة: الهندسة والتكنولوجيا

عنوان الرسالة: ....
The effect of glass plate thickness and interlayer polyvinyl butyral (P.V.B.) thickness on fracture and Penetration resistance in laminated glass

اعلن بأنني قد التزمت بقوانين الجامعة الأردنية وأنظمتها وتعليماتها وقراراتها السارية المفعول المتعلقة باعداد رسائل الماجستير عندما قمت شخصيا" باعداد رسالتي وذلك بما ينسجم مع الأمانة العلمية وكافة المعايير الأخلاقية المتعارف عليها في كتابة الرسائل العلمية. كما أنني أعلن بأن رسالتي هذه غير منقولة أو مستلة من رسائل أو كتب أو أبحاث أو أي منشورات علمية تم نشرها أو تخزينها في أي وسيلة اعلامية، وتأسيسا" على ما تقدم فانني أتحمل المسؤولية بأنواعها كافة فيما لو تبين غير ذلك بما فيه حق مجلس العمداء في الجامعة الأردنية بالغاء قرار منحي الدرجة العلمية التي حصلت عليها وسحب شهادة التخرج مني بعد صدورها دون أن يكون لي أي حق في التظلم أو الاعتراض أو الطعن بأي صورة كانت في القرار الصادر عن مجلس العمداء بهذا الصدد.

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THE EFFECT OF GLASS PLATE THICKNESS AND INTERLAYER POLYVINY BUTYRAL (PVB) THICKNESS ON FRACTURE AND PENETRATION RESISTANCE IN LAMINATED GLASS

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This Thesis was Submitted in Partial Fulfillment of the Requirements for the Master's Degree of Industrial Engineer

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Apr, 2011

COMMITTEE DECISION

This Thesis/Dissertation (The effect of glass plate thickness and interlayer polyvinyl butyral (PVB) thickness on fracture and penetration resistance in laminated glass) was Successfully Defended and Approved on 28/3/2011

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DEDICATION

This thesis would be incomplete without a mention of the support given to me by my late sister, to whom this thesis is dedicated. She was the one who kept my spirits up when everything else had failed me. Without her lifting me up whenever this seemed interminable, I doubt it should ever have been completed.

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THE EFFECT OF GLASS PLATE THICKNESS AND INTERLAYER POLYVINY BUTYRAL (PVB) THICKNESS ON FRACTURE AND PENETRATION RESISTANCE IN LAMINATED GLASS

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ABSTRACT

Laminated glass consists of two or more glass plates bonded together with an elastomeric interlayer, usually polyvinyl butyral (PVB) or Ethyl Vinyl Acetate (EVA). After breakage, the interlayer holds the resultant glass shards in place and, in most cases, the glass remains in the frame when laminated glass fractures. This post-breakage characteristic of laminated glass has made it desirable for use in architectural applications and vehicle windshields for decades because it makes the occupant safer from glass shards than other glazing materials.

In this work the effect of the type of interlayer (PVB) or (EVA), number of layers and thickness of the Glass on the failure strength and absorbed energy are reported and compared with each other. Moreover, this investigation presents mathematical model that accounts for factors that affect laminated glass behavior. The factors include thickness of the glass plate, laminated interlayer, and composition of the interlayer. Both the theoretical model and the new failure strength data indicate that laminated glass absorbed energy increases with the increases interlayer thickness and glass thickness and the laminated glass strength for bending force decreases as interlayer increases

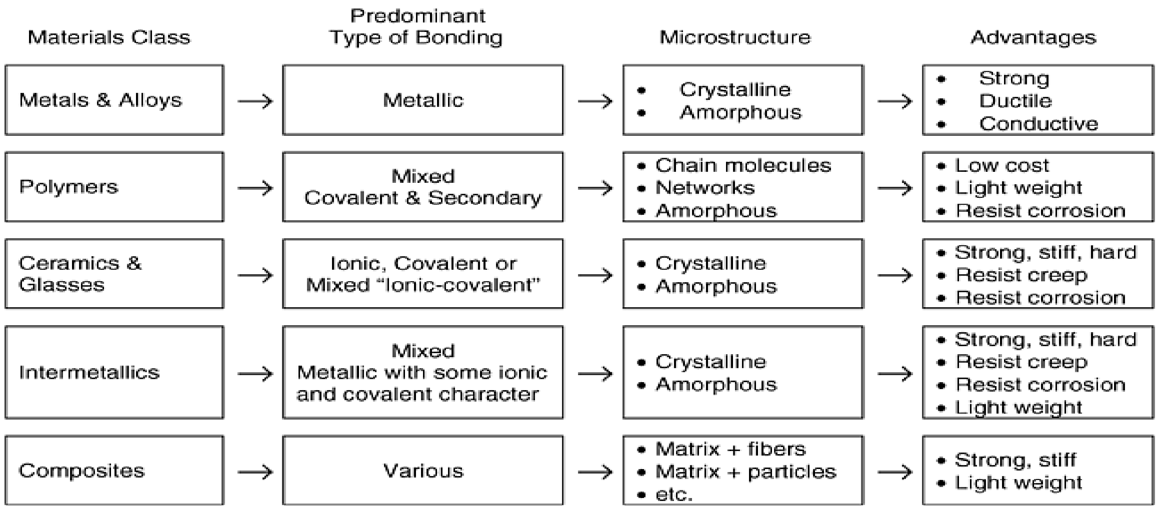
We can used this results and theoretical model to find the suitable laminated glass to resist the force and help in absorbing higher energy in very important in application. For example, high rise building or some open area to high impact wind force.

CHAPTER ONE: INTRODUCTION

1.1 Background

Laminated glass was invented in 1903 by the French chemist Edouard Benedictus, inspired by a laboratory accident. A glass flask had become coated with the plastic cellulose nitrate and when dropped shattered but did not break into pieces. Benedictus fabricated a glass-plastic composite to reduce injuries in car accidents. It was not immediately adopted by automobile manufacturers, but laminated glass was widely used in the eyepieces of gas masks during World War I.

The interlayer and annealed glass are the main engineering material components in the manufacture of laminated glass. In general Engineering materials can be conveniently grouped into five broad classes: metals, ceramics and glasses, intermetallic compounds, polymers, and composite materials. As Adapted of Dowling (1993) , in fig (1).



Figure(1): General characteristics of major classes of engineering materials.

Ceramics and glasses, which have strong ionic-covalent chemical bonds, are very strong and stiff (i.e., they have large elastic module). They are also resistant to high temperatures and corrosion, but are brittle and prone to failure at ambient temperatures.

In contrast, thermoplastic polymers such as polyvinyl butyral, which have weak secondary bonds between long chain molecules, exhibit low strength, low stiffness, and a susceptibility to creep at ambient temperatures. These polymers, however, tend to be extremely ductile at ambient temperatures. When combine glass and polymer to form a laminated glass, some changes in the failure strength will occur, which depends on both the glass and polymer.

In most cases, designers of architectural glazing follow procedures provided by model building codes to design window glass. These codes commonly use design charts to determine design strength based on nominal glass thickness and aspect ratio. The type factor multiplies by the design strength to account for glass constructions that might increase or decrease the strength of the glazing product. For example, a type factor of 4 is commonly used for fully tempered glass, indicating that a fully tempered glass is four times stronger than an annealed, monolithic glass having the same rectangular dimensions and nominal glass thickness. Depending upon the model building code or design recommendation used, the design strength for a laminated glass lies between 45 percent and 90 percent of the strength of a monolithic glass having the same nominal thickness and rectangular dimensions (SBCCI, 1985; UBC, 1994; BOCCA, 1990; and ASTM 1994).

Laminated glass after breakage remains in the frame. This post-breakage characteristic makes laminated glass an excellent safety glazing material for architectural applications. In fact, most usage of laminated in architectural applications derives directly from provisions in model building codes that require a safety glazing material. Because of the

reduction in laminated glass design strength by most building codes and design recommendations, designers avoid architectural laminated glass applications, other than for safety considerations. The most common argument proffered against laminated glass contends that laminated glass has lower strength than monolithic glass, making it uneconomical. The argument against laminated glass, that lowers its strength, persists in spite of voluminous data from experimental research to the contrary.

The strength argument persists, in part, because no rational model exists that provides an adequate explanation of the experimental data. The argue here is when it is suitable to increase the glass thickness and add more interlayers to the laminated glass.

In this reasarch destructive testing will by presented to determine the effect of the bonding layer type,number,thicknessof glass and the position of glass plates on the bending resistance and absorbed energy.furthermore, this investigation present a mathematical model that relats the maximum bending force of the glass laminated structure to the glass plate thickness,type and thickness of interlayer regardless the position of fixed glass plate.

1.2 Objectives

The objective of this research is to find how the glass thickness and the number of laminated interlayer affect the absorbed energy as well as their effect on bending resistance.

Also finding out the difference between the use of (PVB) interlayer and (EVA) interlayer, and compare the effect of each type on absorbed energy to fracture and bending resistance.

Unlike previous works, in this investigation two type of interlayer (EVA) and (PVB) are used for laminated glass. In addition theoretical mathematical model will be determined to show the experimental results.

And finally Makeing practical recommendations for best combination to meet the required specifications based on the results.

1.3Thesis Outline

In chapter one background about glass and laminated glass is presented, and also the objectives of this research are included in it.

The second chapter explains glass manufacturing and processing, while Chapter three reviews previous research accomplished concerning laminated glass strength.

All material and equipment used in all the experimental procedures will be discussed in chapter four. Chapter five presents the test results, observations and discusses final findings of this research.

Finally, chapter six includes the conclusion and recommendations.

CHAPTER TWO: GLASS MANUFACTURING

There are two main flat glass manufacturing methods for producing the basic glass form (Button and Pye1993) .These methods are presented in the following sections.

2.1 BASIC GLASS MANUFACTURING

There are two approached for basic glass manufacturing. ; float and rolled.

2.1.1 FLOAT

More than 90% of the word's glass is made by the float process. Molten glass, at approximately 1000 C^o, is poured continuously from a furnace on to large shallow bath of molten tin. It floats on the tin, spreads out and forms a level surface. Thickness is controlled by the speed at which the solidifying glass ribbon is drawn off the bath. After annealing the glass emerges as a 'fire' polished product with virtually parallel surfaces.

2.1.2 ROLLED

The rolling process make patterned, figured and cast glass products, whereby a semi-molten glass is squeezed between metal rollers to produce a ribbon with controlled thickness and surface pattern.

2.2. MODIFIED BASIC MANUFACTURE

Broadly, there are three forms of modification to the above basic manufacturing processes (Button and Pye1993).

2.2.1 TINTED

Body tinted glass products are products by small additions of metal oxides to float or rolled glass composition. These small additions color the glass bronze, green, blue or grey but do not affect the basic properties of glass except for changes in the solar transmission.

2.2.2 COATED (ON-LINE)

Modified properties are produced from the basic glass by means of surface coating applied, in this case, on-line during the basic manufacture. They have advantages of hardness and durability over off-line coating applied after the basic manufacture. Coatings may modify some or all of solar energy transmission, color, and thermal insulation properties.

2.2.3 WIRED

Wired glass is made by rolling process. In one such process, a steel wire mesh is sandwiched between two separate ribbons of glass and passed through a pair of consolidating rollers which may also impress a required pattern. The rough cast surface may be polished to obtain clear transparency. Its uses may be in fire resistance and safety glazing

2.3 PRIMARY PROCESSING

Primary process is treatment on the basic glass after its manufacture (Button and Pye(1993).

2.3.1 HEAT TREATED

Toughened glass, or tempered glass as it is also known, is produced by heating annealed glass to approximately 650 C^o, at which point it begins to soften. Its outer surface is then cooled rapidly, creating in them a high compression. Its bending strength is usually increased to factor 4 or 5 that of annealed glass. When broken, it fractures into small harmless dice and is deemed a safety glazing material. Heat strengthened glass is similarly produced, but with strengths approximately half that of toughened glass and without the safety glazing characteristic.

2.3.2 BENT

Bent glass is produced by heating annealed glass to appoint where it softens so it can be or sag bent over formers.

2.3.3 SURFACE WORKED

Fine surface textures are applied by varying degrees and varieties, using sand blasting and acid etching.

Deeper textures, cuts and designs are produced by engraving, using an abrasive copper wheel, a diamond point or a carborundum pencil. They may be factory or hand applied, and the glass may be subsequently heat treated or bent.

2.4 SECONDARY PROCESSING

This is defined as adding extrinsic additional materials or components to the basic glass after its manufacture (Button and Pye1993).

2.4.1 PRINTED

Ceramic ink designs are screen printed on to float glass which is then toughened, fusing the ink to the surface and providing a permanent durable finish. These products may meet requirements of aesthetics, solar control and information display.

2.4.2 COATED (OFF-LINE)

This coating is applied to individual plates of glass after manufacture be means of chemical solution vacuum evaporation or magnetron sputtering, producing solar optical and thermal insulation properties similar to on-line coatings. Silvering is a form of coating, but is not included in this discussion.

2.4.3 MULTIPLE GLAZED UNITS

Multiple glazed units incorporate two (or more) panes, separated by a spacer (or spacers), to create a hermetically sealed gap between each successive pane in the unit. This gap can be filled with air which is subsequently desiccant dried. Low emissivity coating can be added to one or more interior glass surface in multiple glazed unit to provide thermal insulation. The further enhance the thermal insulation properties, low conductivity gases such as argon can be used instead of air in the cavities. Other gases (primarily sulphur hexafluoride) can similarly be used to improve acoustic insulation. The panes are usually connected by a spacer using sealant to give mechanical strength and to resist air or water penetration.

2.4.4 LAMINATED

Laminated glass is produced by bonding two or more panes of glass together with plastic material, a resin or in tumescent interlayer. Laminated can incorporate most thicknesses of glass and plastic to give a selection of products with arranged mechanical, fire resistance and optical properties.

Laminated glass can incorporate other materials, such as polycarbonates, to achieve specific mechanical performances. When laminated glass is broken the interlayer tends to hold the fragments of broken glass in place, and it may be deemed a safety glazing material

Laminated glass is a combination of two or more glass sheets with one or more interlayers of plastic (PVB) or (EVA) (which can be uncolored and transparent or colored, xerigrafato, and so on) or resin. The first provides good adhesion to glass and a high level of lengthening before breaking.

The layer of PVB and EVA keep the pieces of glass in place, reducing the risk of cuts caused by splinters and absorbing the body’s residual energy, thereby preventing the

body's entry through the glass unless it is by an exceptional force. This glass is particularly suitable where it is important to ensure the resistance of the whole sheet after breakage.

Laminated glass is used as

(a) safety windows in windshields for cars, trains, airplanes, and so on.

(b) in glass walls to resist any falls of people or things but also as protection against vandalism and breaking and entering.

(c) as strengthened protection for art objects in museums.

(d) against explosions and bullet-shots (armored glass).

Laminated Glass Production:

There are two types of laminated glass: filem layer and resin-laminated glass.

A. Film layer *Laminated*

Two or more sheets of glass that are bonded together with one or more layers under heat and pressure to form a single piece.

Traditional laminated glass is made out of PVB interlayer film. It is final bonded with autoclave which is a necessary air pressure vessel to produce laminated glass with PVB interlayer or any other films that require bonding under pressure . Autoclave is always incorporated to laminating line with pre-assembly, pre-heating or pre-vacuum process. Melting of interlayer films and final bonding of laminated glass are accomplished in autoclave.

A new type of glass laminating technology, in one stage, is developed. Without vacuum bags, rubber rings, and autoclave.. EVA interlayer, made of ethyl vinyl acetate copolymer resin, is the most popular plastic film for laminated glass production free of autoclave. All materials, including glass and EVA film, are lay up and well assembled. It

is then put inside the oven for heating under vacuum. The EVA becomes melted and bond the glass.

B . Resin-laminated

Glass is manufactured by pouring liquid resin into the cavity between two sheets of glass that are held together until the resin cures.

Resin laminated glass will be combined with a special laminating resin that will be cured under UV lamps. It is possible to use different glass types by laminating (float glass, patterned glass, lacobel etc.) and mirrors.

The resin fill process involves minimum initial capital investment, and is arelatively easy, flexible manufacturing process. This method allows for variation in resin thickness, where standard thickness of the resin layer by the laminating of 3-6 mm glasses is 1 mm, by 8-12 mm glasses 1,5 mm.

CHAPTER THREE: LITERATURE REVIEW

The interaction between the properties of the interlayer glass thickness was studed by Quenett (1967). He noticed that as the interlayer thickness decreases, shear modulus increases. He also reported the condition of the interlayer is a controlling factor in static bending and dynamic impact resistance.

The study was carried out by Hooper (1973) confirmed the results of Quenett. He found the shear modulus of the interlayer to be inversely proportional to the interlayer thickness in tests performed on glass beams and attributed this behavior to the "thermoplastic" nature of the interlayer, stating the decreased bending stiffness was the primary disadvantage to architectural laminated glass. Hooper tested glass beams in four point loading with varying temperatures and interlayer harnesses. He also cited plasticizer contents, ambient temperatures, and load durations as the primary factors controlling bending resistance of laminated glass.

Pilkington, Ltd.(1971) compared monolithic glass strength to the strength of laminated glass specimens made of sheet and float glass. They found that, at normal temperature, laminated glass specimens exhibit the same strength as monolithic glass specimens having the same rectangular dimensions and glass thicknesses.

Linden et al. (1983) conducted non-destructive testing on monolithic, layered, and laminated glass specimens instrumented with strain gages. They also derived theoretical results through a finite difference solution and compared experimental and theoretical results. They drew three conclusions:

(1) the theoretical finite difference model for monolithic and layered glass appeared to be acceptable for the one glass plate geometry tested;

(2) laminated glass strength and monolithic glass strength appeared to be equivalent at normal temperatures; and

(3) the strength of laminated glass specimens approached that of layered glass specimens at elevated temperatures.

A year later Linden, Minor, and Vallabhan (1984) reported additional research in a supplement. They conducted non-destructive testing on two different plate geometries. First, they tested the same plate geometry (60 x 96 x 1/4 in.) as used in the parent report to study load duration and temperature effects. Second, they tested a different geometry (55-1/8 x 57-1/8 x 3/8 in.) with two interlayer thicknesses (0.030 and 0.060 in.) to study the effects of interlayer thickness on strength and deflection. They conducted destructive tests on one plate geometry (60 x 96 x 1/4 in.) at room temperature and at 170°F. Perusal of their data indicates that while load duration and elevated temperatures acting individually reduce the structural rigidity of the laminated glass, the two factors do not interact, producing a greater combined reduction in laminated glass strength.

Non-destructive experiments on the square specimens indicated that greater interlayer thickness slightly reduced the stiffness of the laminated glass specimens. In destructive testing, laminated glass specimens tested at room temperature were 22 percent stronger than monolithic having the same rectangular dimensions and nominal glass thicknesses.

Laminated glass specimens tested at 170°F had a mean failure strength below monolithic glass specimens having the same rectangular dimensions and nominal glass thicknesses, and had a failure strength above theoretical failure pressures for layered glass specimens. Nagalla, Vallabhan, Minor, and Norville (1985) advanced theoretical work comparing layered glass to monolithic glass. They discovered that some aspect ratios of the layered glass experienced lower principal stresses than monolithic glass subjected to uniform, transverse loading in some ranges of the loading. The implication is that certain laminated glass will display greater strength than monolithic having the same rectangular dimensions and nominal glass thickness due to the combination of flexural stresses and

membrane stresses alone. They concluded that the strength factor of 0.6 used by some building codes for laminated glass may be too low for many window geometries and design pressures.

Reznik and Minor (1986) destructively tested three sizes of laminated glass specimens (33 x 66, 38 x 76, and 66 x 66 in.) with an 0.030 in. interlayer, and compared the resulting failure pressures to those from tests on monolithic glass specimens having the same rectangular dimensions and nominal glass thicknesses. They introduced four variables besides rectangular dimensions:

(1) Glass thickness (1/4 and 1/2 in.);

(2) glass type (annealed, heat strengthened, and fully-tempered);

(3) temperature (room temperature, 120°F, 170°F); and

(4) damage to one plate of glass (i.e., damage to tension or compression side).

The testing led to the following conclusions:

(1) laminated glass specimens tested at room temperature have approximately the same failure pressure as monolithic glass specimens having the same rectangular dimensions and nominal glass thicknesses;

(2) as temperature increases laminated glass behavior migrates towards the layered glass model.

(3) laminated glass specimens having twice the nominal glass thickness of monolithic specimens display strength greater than or equal to twice the strength of the monolithic specimens.

Reznik and Minor's results are consistent with Norville's (1990). Norville tested two laminated glass specimen sizes destructively (38 x 76 and 66 x 66 in.). His destructive experimentation also showed the strength of laminated glass specimens to be the same or greater than that of monolithic specimens having the same rectangular dimensions and

nominal thicknesses under similar load conditions. Behr, Minor, and Norville (1993) provided a thorough synopsis of destructive testing, non-destructive testing, and theoretical analyses of laminated glass. They performed non-destructive tests on laminated glass beams simply supported on two sides at three different temperatures (32°F, 74°F, and 120°F). They loaded glass beams to 58 psf in 14.6 psf increments, while recording deflections and stresses at each increment. Behr, Minor, and Norville (1993) hypothesized that when the aspect ratio exceeded a certain value the short rectangular direction carried the majority of the load; therefore, traditional testing methods with the glass simply supported on four sides, would not describe adequately laminated glass behavior for these aspect ratios. Their research revealed that even at high aspect ratios laminated glass behaves like monolithic glass having the same rectangular dimensions and nominal glass thicknesses.

A theoretical, non-linear model for laminated glass as sandwich plates was developed by Das and Vallabhan (1988) ,They determined that this model was too complex to be practical.

Vallabhan et al. (1993) advanced a second non-linear mathematical model for a single laminated glass geometry (60 x 60 x 3/8 in.). They solved the non-linear differential equations by a finite difference, iterative procedure and compared the results to non-destructive testing data. The full-scale experiments confirmed the second model's ability to predict stresses in a laminated glass specimen having that particular geometry.

Behr and kremr (1999)used experimental validation of a mechanics-based finite element model for architectural laminated glass units subjected to low velocity, two gram projectile impacts is described. The impact situation models a scenario commonly observed during severe windstorms, in which small, hard projectiles, such as roof gravel, impact windows. Controlled experiments

This study confirmed the ability of an analytical finite element model to predict accurately the peak strains in representative architectural laminated glass units as functions of impact velocity, laminate configuration, and component material properties. Correlations between peak radial strains computed using finite element analysis and those measured experimentally were close, with the average difference between analytical. predictions and experimental data being 7.7%. Peak radial strain increases significantly as projectile impact velocity is increased, and peak radial strain decreases significantly as glass plate thickness is increased. Peak radial strain decreases only slightly, however, as PVB thickness is increased, and peak radial strain (or, more precisely, the increment of peak radial strain due to projectile impact) is unaffected by the existence of a state of compressive pres tress on the glass surface—as exists in heat-strengthened and fully tempered glass. Thus, net glass surface stresses due to heat treatment during manufacture and projectile impacts during service can be obtained by straightforward algebraic superposition of these stresses.

The successful experimental validations of finite element computations performed in this study accomplished an important step toward developing a comprehensive, mechanics-based, failure prediction model for laminated glass units under low velocity projectile impacts such as those encountered during severe windstorms. Specifically, strains and stresses computed by finite element analysis will be related to the probability of inner glass plate failure in laminated glass units under windborne debris impacts. Then, a design procedure will be developed for architectural laminated glass units wherein only the outer (exterior) glass plate is broken during windborne debris impacts. Provided that the unbroken inner glass plate is designed for the appropriate lateral wind pressures, the resulting “sacrificial plate” laminated glass units will improve significantly the overall resistance of building envelope systems to the ravaging effects of severe windstorms.

Zang andWang (2007) study focused on useing the 3D discrete element method to study the impact fracture problem of laminated glass. The glass and the (PVB) of laminated glass plane are discretized to the assembling of uniform rigid spherical elements. This investigation gave the follow.

1. The accuracy of the 3D model and numerical analysis code are more validated in the elastic range by comparing with FEM.

2. The impact fracture processes of a single glass plane and a laminated glass plane are simulated by using the code.

The very complex and highly nonlinear behavior under applied pressure due to the effect of geometry that undergoes large deflection and order difference in modulus of elasticity of glass and PVB was explain by Mehment (2003). His Results dictate that the nonlinear analysis of laminated glass is the only acceptable analysis. Geometric stiffness due to the geometric nonlinearity incorporated in the solution of laminated glass units affects the results substantially. Location of maximum stress starts to travel at the center, follows two perpendicular symmetry axes, then travels on the diagonal of the unit and then moves towards the corner of the plate ,when the nonlinear terms, start to be affected under increasing pressure. One of the principal stresses changes its direction on each surface. Complex stress fields develop near the edge supports and corners.

Weller (2005), Used experimental study to compare different interlayer materials in laminated glass in respect of their structural behaviour.

The material properties above the verification temperature clearly show the temperature dependency. The relaxation times fall with increasing temperature and the shear stress gets smaller.

The comparison of PVB and EVA test results offers quite a surprising figure. In the temperature range of more than 25 °C, the shear strength of the EVA-layer specimen is

definetely higher than the shear strength of the PVB-layer specimen. Only if the temperature of the PVB falls below the vitrification temperature, a noticeable stiffening could be observed. At a temperature of 10 °C and below, the test results showed a better shear stiffness of the PVB.

Nourry (2005) study the fracture behavavior during hard body imapact, analysis of the energy balance of the hard body impact on laminated glass confirms the small part of energy degraded by fragmentation and projection of glass fragments. The interlayer deformation, governed by the properties of adhesion, dissipates the major part of the kinetic energy of the impactor.

Keller (2005) used novel method to measure the delaminating energy in laminated glass is the relevant dynamic range. find the increasing the interlayer thickness improves the penetration resistance of laminated because more energy can by absorbed in the high speed delimitation process since the interlayer is simplys less like to tear.

Belies (2008) compared (PVB) with stiffer and stronger interlayer SentryGlas plus (SGP) After breakage of both glass sheets the load decreased to a relatively low level (typicallybetween 2 kN and 3 kN) before the broken glass pieces and interlayer started again to build up compressive and tensile stresses, respectively. Subsequently, the load slightly increased again and after reaching a (sometimes barely noticeable) maximum, it decreased significantly (to less then 0.3 kN). When subjected to in-plane bending (buckling prevented), the post breakage residual resistance is relatively poor for both interlayers, as illustrated above. The residual load-bearing capacity was very limited and far below the initial glass strength.

An experimental study was carried out by Pankhardt (2008) to analyse the effect of tempering and influence of interlayer material and temperature on the structural behaviour of glass pane. The results of these experiments can be thus summarized as before the

fracture of glass pane the deflections can be high especially in the case of single glass. Deflections of glass pane should be limited also because of the sealing and watertightness, and not to override the adhesion strength by large deformations of glass panes.

The stresses, compared to surface tension stresses, have shown that in-plane stresses lead earlier to failure than bending stresses, especially in the case of thin glass panes.

By increasing temperature of glass specimens, the measured strains on lower surface increased in both Regions. Edge stresses are always about 10% higher than the mid pane stresses. Reaching the maximum value of strains in edge region the fracture occurred, therefore the effect of the edge quality is important on load bearing and durability of glass. The decrease of the edge stresses decreases the load bearing capacity.

The remaining stability of glass depends also on the interlayer. The maximal load bearing capacity and load bearing capacity after fracture (post-failure behaviour) of the glass should be also obtained when glass is used in "first ordery" structures such as beams, columns, slabs or when it is used in overhead areas like roofs or canopies where high safety demands have to be granted.

It is clear from previous work the research work focused on the comparing between the strength of monolithic and laminated glass and did not take into consideration the bonding interlayer thickness, and the position and thickness of glass plate. Furthermore, main bonding material in this studies is (PVB).

This investigation differs from previous in that it concentrates on how the glass thickness and type and number of laminated interlayer affect the maximum bending force of laminated glass as well as their effect on the absorbed energy . In addition theoretical mathematical model will be determined to show the experimental results.

CHAPTER FOUR: MATERIAL, EQUIPMENT AND EXPERIMENTAL PROCEDURE

4.1 Materials

The materials used in this investigation are:

1- Float glass plates

2- Laminated interlayers material which are :

A-Polyvinyl Butyral (PVB).

B- Ethylene Vinyl Acetate (EVA).

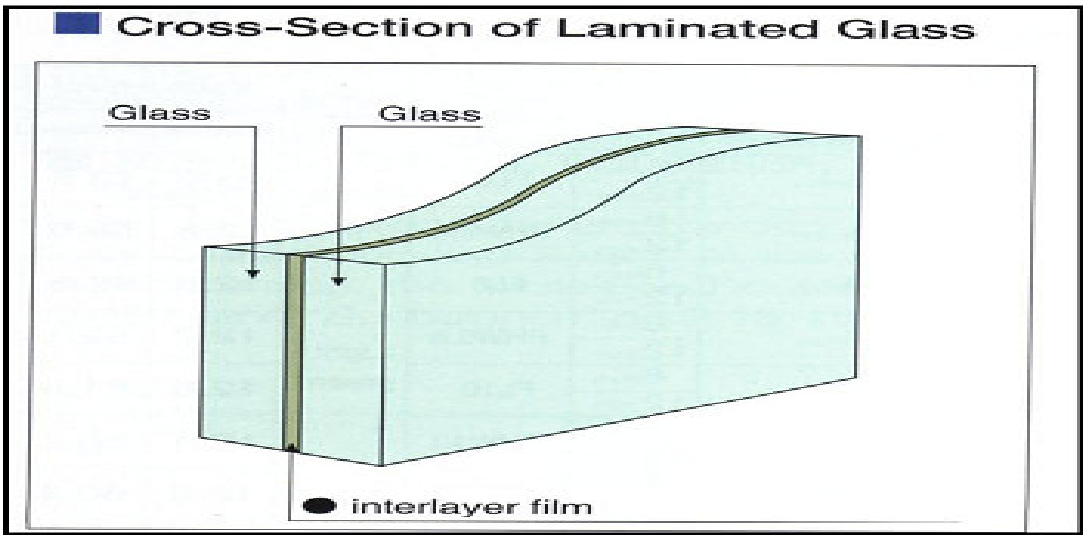


Figure (2) :glass material cross section

4.1.1 Float Glass Plate

Glass is a liquid that has cooled to rigid state without crystallizing. It is sometimes described as a 'supercooled liquid'. A supercooled liquid is still a liquid at a temperature below that at which it would normally solidify. Glass is solid with an amorphous random or non-crystalline structure. The use of the term 'supercooled liquid' suggests the idea of flow, but in fact glass is far too rigid to flow at normal temperature, however long a force is applied to it.

The application of a force to material results in a slight deformation, whilst at the same time internal force developed in order to resist this deformation. The deformation induces strain (stretching or compression) while the internal force per unit area are know as stress. These arise whenever a force is applied to solid material.

When a material is stressed it deforms by the stretching of the interatomic and intermolecular bonds and, at low levels of stress, the strain is proportional to the stress. At higher levels of stress most materials deform plastically, that is the atoms or molecules in the structure become rearranged or crystals slide past each other. These material can often accommodate large strains without failure, but the structure of glass cannot accommodate this plastic deformation, so the stress-strain curve for glass show perfect linearity. This is rare among common materials.

The theoretical strength of piece of flat glass should (on atomic bond strength calculation) be around 21000 N/mm^2. On freshly drawn glass fibres, tensile stresses of up to 5000 N/mm^2 have been measured and, even when incorporation into a resin to form glass reinforced plastic, glass fibres have a usable stress of about 1200 N/mm^2. However, window glass usually fails at stress levels less than 100 N/mm^2 Button and Pye(1993). In practice, therefore, the amount of stress needed to start crack in glass is very much less than expected considering the forces needed to break the interatomic bonds. There is some form of stress concentration factor at work.

In 1921Griffitg first put forward the idea that the surface of any glass is liberally provided with invisibly small defects (Griffith flaws), any one of which may, under suitable condition, concentrate the applied stress on to the interatomic bonds in the defect and cause them to break,thus propagation of crack and leading to failure. It is now understood that the stress needed to cause failure depends on the number of Griffith flaws and on the presence in the flaws of chemicals, including water, which may attack the

strained atomic bonds. The presence of Griffith flaws appears to be attributable to contamination of the surface by particles of dust and moisture vapor.

The strength of glass is also modified by the presence of larger surface flaws. Under stress these can be origin of cracks since the glass may be unable to accommodate the local stress concentrations they cause. The presence of these flaws is one reason why the edge region of a piece of glass is usually weaker than the face surface. It is much more prone to damage form accidental contact with the surroundings.

The position is further complicated by a phenomenon know as 'static fatigue'. This has nothing in common with the more widely know mechanism of dynamic fatigue in metals. The glass may withstand a stress for a short time, which, if it were maintained indefinitely, would cause failure due to corrosion of the strained interatomic bonds at a crack tip. In fact glass can sustain, for a short period if maintained for a long period

In theory, the compressive strength of glass should be around 2100 N/mm^2. In practice, it has not been measured. Any test which has been devised to measure compressive stress produces tensile stresses as side effect. It has not been possible to measure only compressive strength, because the test samples fail due to tensile stress side effect. In effect, glass never breaks from the effect of compressive stress, always from tensile stresses.

Since surface flaws only lead to fracture when a tensile stress opens them, any method of putting the glass surface into permanent compression is advantageous. An applied tensile stress would have to overcome this built-in compression before it begin to open up a flaw and the glass would be able to resist higher loads. Toughened glass and heat strengthened glass use this principle.

The stress distribution in toughened glass enables it to withstand bending stresses to much higher levels than ordinary annealed glass. During production of annealed glass, it

is carefully cooled through the range of temperatures where the glass solidifies so that no significant residual stresses develop. This is necessary so that the glass can be cut or worked . toughened glass cannot be cut or worked. If a crack penetrates the compressive layer of toughened glass into the central tensile region, there is enough tensile stress available to make the crack propagate violently through the glass. This forms the characteristic dice pattern of broken toughend glass. Heat strengthened glass is tempered lower level of stress so that it does not form the characteristic dice pattern ,but it also cannot be cut or worked.

4.1.2 Laminated Interlayer Materials

The interlayer materials which be used in laminated glass are polymers materials. Which are long chain molecules (macromolecules) consisting of a series of small repeating molecular units (monomers). Most common polymers have carbon (organic material). Polymeric materials exhibit strong covalent bonds within each chain; however, individual chains are frequently linked via secondary bonds (i.e., van der Waals, hydrogen, and so on) though cross-linking via primary bonds is possible.

In polymeric materials, secondary bonds arise from atomic or molecular dipoles that form when positively charged and negatively charged regions of an atom or molecule separate. Bonding results from columbic attraction between the positive and negative regions of adjacent dipoles.

Secondary bonds are much weaker than primary bonds, which accounts for the low melting temperatures, low stiffness, and low strength exhibited by many polymers.

Polymers that will be used in this investigation on the laminated glass are :

4.1.2.1 Polyvinyl Butyral (PVB)

PVB is a vinyl polymer and, within this chemical group, can be classified as belonging to the polyvinyl acetates (PVAC). According to the physical classification,

PVB is one of the amorphous thermoplastics. The mechanical thermal behavior of amorphous thermoplastics is described above.

PVB is a solid resin which is soluble in organic solvents but not in hydrocarbons and which is resistant to acids and alkalis. The layers normally used in construction can be made out of this resin. 20 % of their oxygen-hydrogen-groups are unbound which results in a good adhesive strength. The adhesion between the glass and the layer is based on the formation of hydrogen bonds.

Because of the stiffness and the insufficient elastic properties, these layers are changed by adding softeners and additives. Adhesion capacity, elasticity and water-absorbing capacity are influenced by softeners. Typical additives are for example ultraviolet radiation blocker or pigments. The PVB-layers that are usually used in the building industry contain a relatively high quantity of softeners in order to guarantee sufficient toughness and breaking elongation even at low temperatures.

The verification temperature (Tg) of these layers lies between 12 °C and 16 °C depending on the content of the softeners. Concerning amorphous thermoplastics like PVB, a fall in verification temperature will cause significant stiffening and a reduction in elasticity. A temperature between 20 °C and 60 °C is favorable to the useful properties which are characteristic for the PVB-layer in laminated glass.

PVB is the preferred material for the production of laminated safety glass. Usually, PVB-layers and glass are made into laminated safety glass during a two-stage autoclave lamination process. The preferential use of PVB-layers in laminated safety glass is based on the mechanical properties and the excellent splitter bond with the PVB-layer. PVB can reach tearing strength of more than 20 MPa as well as an elongation at fracture of over 250 % at a temperature of 23 °C. The most important properties of PVB are its high transparency and tearing strength, a favorable elongation at fracture, its high breakdown

resistance, an adjustable glass adhesion and a high stability regarding both ultra violet radiation and temperature. The water absorption of PVB is a problem which can cause a worse bonding between PVB and glass.

The films tested in the experimental study are standard PVB-layers in the domain of flat glass.

4.1.2.2 Ethylene Vinyl Acetate (EVA)

Within the group of polymers, EVA belongs to the polyolefines. According to the physical classification, EVA is one of the thermoplastics and it is produced during the copolymerisation of ethylen and vinyl acetate. It can be made from these two monomers in every proportion.

Depending on the composition, the properties vary from partial crystalline and thermoplastic to amorphous and rubber-like. That is why an over-all statement cannot be made. An increased quantity of vinyl acetate results in a higher tearing strength and a better elongation at fracture, but also in a fall of melting temperature.

The EVA-layer used during the series of experiments has a vinyl acetate content of 32 % which was already a sign of favourable mechanical properties. According to the data sheet, the vitrification temperature (Tg) amounts to -43 °C. However, the layers available on the market can exceed a vinyl acetate content of 40 %. In this case, the branching degree of the EVA will increase, so that rubber elastic thermoplastics, the so-called thermoplastic elastomers (consisting of a wide meshed network) are generated.

EVA-Layers are often used as an interlayer material in the domain of solar industry. In this case, and also when being used as an interlayer in laminated glass, modified EVAs are applicated. These layers are called “hot melt adhesive film” and they are characterised by a tearing strength of 10 MPa up to 25 MPa, an elongation at fracture of more than 500 % and an excellent cohesion as well as a good adhesion.

They are also particularly used in order to encapsulate solar modules because the liquefaction of the adhesive during the process of connection corrects the existing unevenness offhand. This feature is particularly important for the crystalline solar cells that are embedded between the two layers of the composite material.

The cross-linking of the EVA-layers happens during the process of lamination. Because of their chemical structure, EVA-Copolymers can easliy be linked either chemically or physically. During the cross-linking process, mainly vinyl acetate units of the molecular strings are chemically attached to each other. At the same time, a spatial network is developing. The chain molecules are more or less assembled inside this network depending on the degree of connection.

In practice, depending on the state of cross-linking, only parts of the molecules are integrated inside the network. Therefore, a spatial net can either be small or wide meshed depending on the degree of cross-linking. Essential characteristics like tearing strength, creep rupture behaviour or chemical resistance can be improved considerably due to the cross-linking and, besides, they can reach a much higher level compared to unconnected EVAs.

Laminated glass results from the connection of glass and EVA during the process of vacuum lamination. Usually, a vacuum laminator with an integrated heating and cooling system is used, so that the heating, the cross-linking of the EVA-layer and the cooling take place in the same apparatus. This is a single-stage process of lamination. Inside the lid of the laminator, a flexible membrane forms a separate chamber which puts the required pressure on the laminate during ventilation.

Throughout the vacuum lamination, the temperature lies between 140 °C and 155 °C depending on the type of film. The duration of the process also depends on the type of film. The so-called “standard curing” EVA takes 40 till 45 minutes, whereas the purpose-

built “fast curing” EVA requires only about 8 till 10 minutes. The size of the vacuum laminator also restricts the formats of the laminated glasses with EVA interlayers and it is defined according to the standard measurements of solar modules

The copolymers of the ethylen can be affected by the weather conditions, especially because of the ultra violet parts of the sun light being under the influence of atmospheric oxygen. This behaviour can lead to a detoriation of the property values, for example the tenacity and the elongation at fracture will decrease and even discolourations may occur. That is why the today´s EVA-layers are provided with stabilisators resulting in a permanant resistance to such outside influences.

4.2 The Variables studied In This Investigation

The material used in this investigation and its variable is shown in the follow tables:

Table 1 for test the maximum force and maximum displacement for (PVB) laminated glass where the thickness of inner plate was fixed and both of outer plate and interlayer thickness was changeable where the one layer thicknss is 0.38 mm.

Table 1 Test samples For Bending Test (PVB) (the outer plates and interlayer thickness changeable)

INTERLAYER *2 THICKNESS (mm)		INTERLAYER *4 THICKNESS (mm)		INTERLAYER *6 THICKNESS (mm)	
Inner plate (mm)	Outer plate (mm)	Inner plate (mm)	Outer plate (mm)	Inner plate (mm)	Outer plate (mm)
4	4	4	4	4	4
4	6	4	6	4	6
4	8	4	8	4	8
4	10	4	10	4	10
4	12	4	12	4	12

Table 2 for test the maximum force and maximum displacement for (PVB) laminated glass where the thickness of outer plate was fixed and both of inner plate and interlayer thickness was changeable.

Table 2 Test samples For Bending Test (PVB) (the inner plates and interlayer thickness changeable)

INTERLAYER *2 THICKNESS (mm)		INTERLAYER *4 THICKNESS (mm)		INTERLAYER *6 THICKNESS (mm)	
Inner plate (mm)	Outer plate (mm)	Inner plate (mm)	Outer plate (mm)	Inner plate (mm)	Outer plate (mm)
4	4	4	4	4	4
6	4	6	4	6	4
8	4	8	4	8	4
10	4	10	4	10	4
12	4	12	4	12	4

Table 3 for test the maximum force and maximum displacement for (EVA) laminated glass where the thickness of inner plate was fixed and both of outer plate and interlayer thickness was changeable

Table 3 Test samples For Bending Test (EVA) (the outer plates and interlayer thickness changeable)

INTERLAYER *2 THICKNESS (mm)		INTERLAYER *4 THICKNESS (mm)		INTERLAYER *6 THICKNESS (mm)	
Inner plate (mm)	Outer plate (mm)	Inner plate (mm)	Outer plate (mm)	Inner plate (mm)	Outer plate (mm)
4	4	4	4	4	4
4	6	4	6	4	6
4	8	4	8	4	8
4	10	4	10	4	10
4	12	4	12	4	12

Table 4 for test the maximum force and maximum displacement for (EVA) laminated glass where the thickness of outer plate was fixed and both of inner plate and interlayer thickness was changeable.

Table 4 Test samples For Bending Test (EVA) (the inner plates and interlayer thickness changeable)

INTERLAYER *2 THICKNESS (mm)		INTERLAYER *4 THICKNESS (mm)		INTERLAYER *6 THICKNESS (mm)	
Inner plate (mm)	Outer plate (mm)	Inner plate (mm)	Outer plate (mm)	Inner plate (mm)	Outer plate (mm)
4	4	4	4	4	4
6	4	6	4	6	4
8	4	8	4	8	4
10	4	10	4	10	4
12	4	12	4	12	4

Table 5 for test the absorbed energy for (PVB) laminated glass where the thickness of inner plate was fixed and both of outer plate and interlayer thickness was changeable.

Table 5 Test samples For Charpy Test (PVB)

INTERLAYER *2 THICKNESS (mm)		INTERLAYER *4 THICKNESS (mm)		INTERLAYER *6 THICKNESS (mm)	
Inner plate (mm)	Outer plate (mm)	Inner plate (mm)	Outer plate (mm)	Inner plate (mm)	Outer plate (mm)
4	4	4	4	4	4
4	6	4	6	4	6
4	8	4	8	4	8
4	10	4	10	4	10
4	12	4	12	4	12

Table 6 for test the absorbed energy for (EVA) laminated glass where the thickness of inner plate was fixed and both of outer plate and interlayer thickness was changeable.

Table 6 Test samples For Charpy Test (EVA)

INTERLAYER *2 THICKNESS (mm)		INTERLAYER *4 THICKNESS (mm)		INTERLAYER *6 THICKNESS (mm)	
Inner plate (mm)	Outer plate (mm)	Inner plate (mm)	Outer plate (mm)	Inner plate (mm)	Outer plate (mm)
4	4	4	4	4	4
4	6	4	6	4	6
4	8	4	8	4	8
4	10	4	10	4	10
4	12	4	12	4	12

4.3 Euipments

Test Facility

1- Glass cutting machine BSJ-NL3725. showen in figure (3)

2- Bend test machine OUTOGRAPH AG – 1S. shown in figure (4)

3- Charpy test machine. showen in figure (6)

4- Maicrometar.

4.4 Experimental Procedure

The test procedure can be summarized as follows:

1-cutting 400 mm x 300 mm from glass panels of (4 mm ,6 mm , 8 mm ,10 mm , 12 mm) thickness as shown in figure (2.A). The sharp cut edges have been broken off or beveled with a grinding tool.

Figure (3): Glass cutting machine BSJ-NL3725.

2- Manufacturing of PVB-laminated glass as follows.

a- First the individual glass sheets are washed,

b- The film is layered in between two glass sheets by using roller process

c- The assembly is heated and pressed (pre-lamination)

d- The assembly full-surface bond is created in an autoclave using high pressure and temperatures of about 140 °C and 10 bar. The interlayer becomes a viscous liquid at this temperature and pressure, and any remaining air dissolves into the laminate layer

2- Manufacturing of EVA-laminated glass as follows:

a- First the individual glass sheets are washed,

b- The film is layered between two glass sheet .

c- The assembly is headed in single stage process of laminated (vacuum with integrated heating and cooling in the same apparatus)

3- Both of laminated glass type cut to required size by using cutting machine.

a- For point bend test rectangular (80mm x 300mm).

b- For charpy test rectangular (20mm x 300mm)

4- Point Bend Testing:

The test is carried out in accordance with ASTM standard D790-03. A small beam of rectangular cross section (300 mm x 80 mm) is placed on two supports. A displacement is applied at its center and the resulting force is recorded. This test is performed on the testing machine where the three point fixture is attached to the machine as shown in Figure (4) & (5).

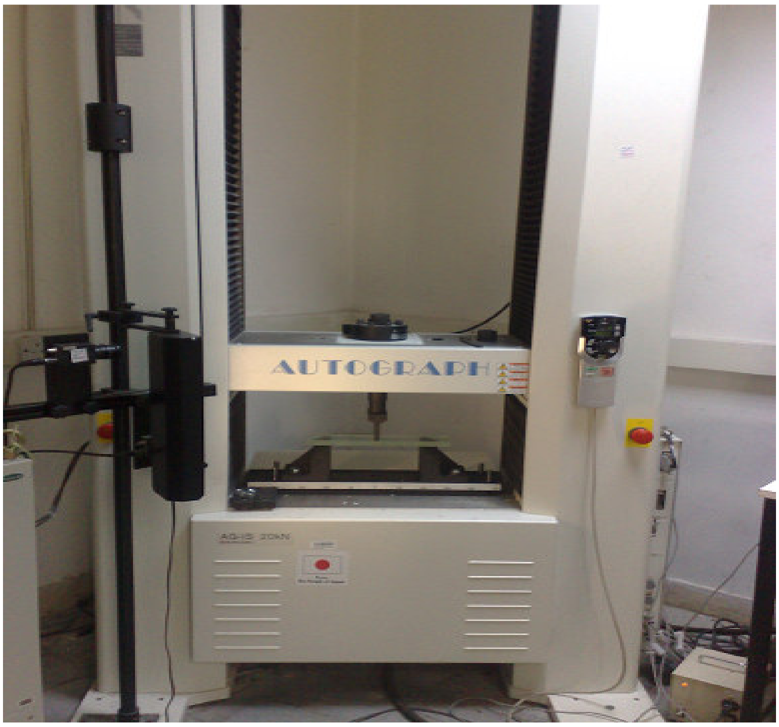


Figure (4): OUTOGRAPH AG – 1S machine for analysis for three point test.

Care was taken to align the specimen correctly. During the loading of the specimen we carefully watched the sample for the first cracks to form and monitor the loads and the load vs. displacement graph. The test was stopped after the sample broke completely or before the fractured sample touched the base of the three point bend fixture. Load vs. displacement data was obtained from the data acquisition system connected to the OUTOGRAPH AG – 1S machine for analysis.

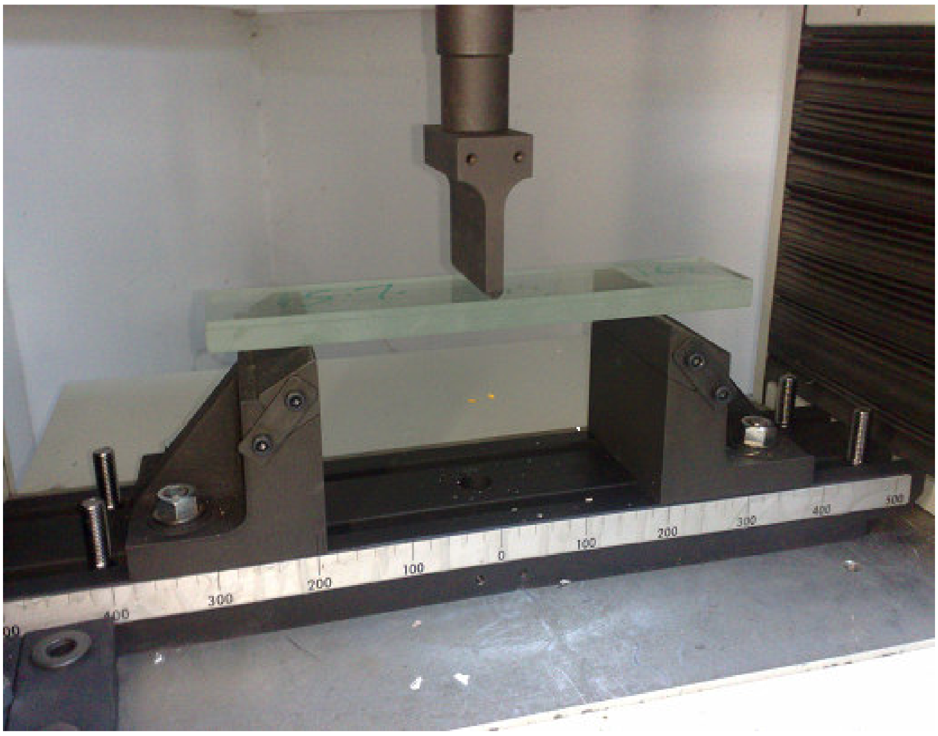


Figure (5): laminated glass tested sample on OUTOGRAPH AG – 1S machine for analysis for three point test

5 - The Charpy testing.

The specimen in the Charpy test is supported on both ends and is broken by a single blow from a pendulum that strikes the middle of the specimen on the unnotched side. The specimen breaks at the notch, the two halves fly away, and the pendulum passes between the two parts of the anvil. The height of fall minus the height of rise gives the amount of energy absorption involved in deforming and breaking the specimen. To this is added frictional and other losses amounting to 1.5 or 3J (1 or 2 ft · lbf). The test is carried out in accordance the Keller (2005) research which is according to EN ISO 8256 .The instrument is calibrated to record directly the energy absorbed by the test specimen.

Figure (6): laminated glass tested sample on charpy tested machine

1- Tested absorbed energy for (PVB) laminated glass where the thickness of inner plate was fixed and the interlayer was changeable.

2- Tested absorbed energy for (EVA) laminated glass where the thickness of inner plate was fixed and the interlayer was changeable.

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CHAPTER FIVE: RESULTS AND DISCUSSION

5.1 Bending Test Results and Discussion

Testing the maximum force on (PVB) laminated glass where the thickness of inner plate was fixed and the outer plate and interlayer were changeable.

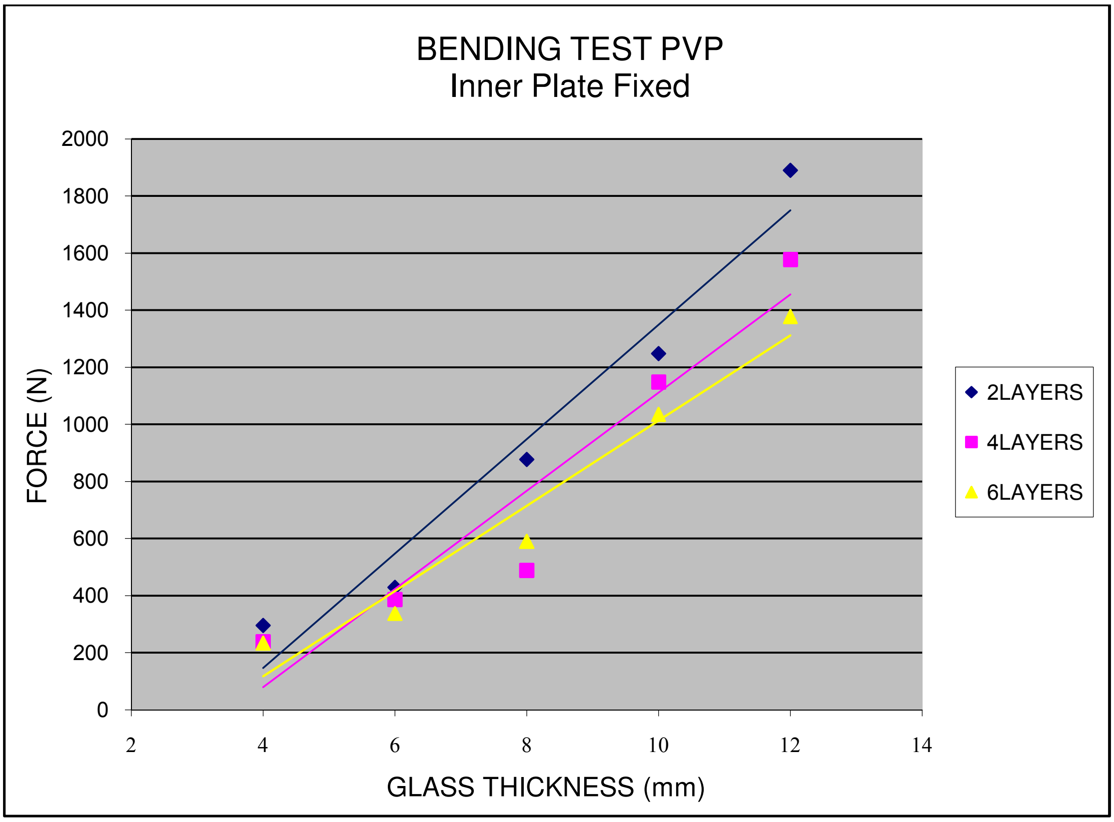

Figure (7): Testing the maximum force on (PVB) laminated glass where the thickness of inner plate was fixed and the outer plate and interlayer were changeable.

The results showed the following:

The effect of changing the thickness of the glass on the maximum value of force the graph shows a proportional relation while the change in thickness of laminated interlayer of the glass caused a decrease in the flexural force.

Testing the maximum force on (EVA) laminated glass where the thickness of inner plate was fixed and the outer plate and interlayer were changeable

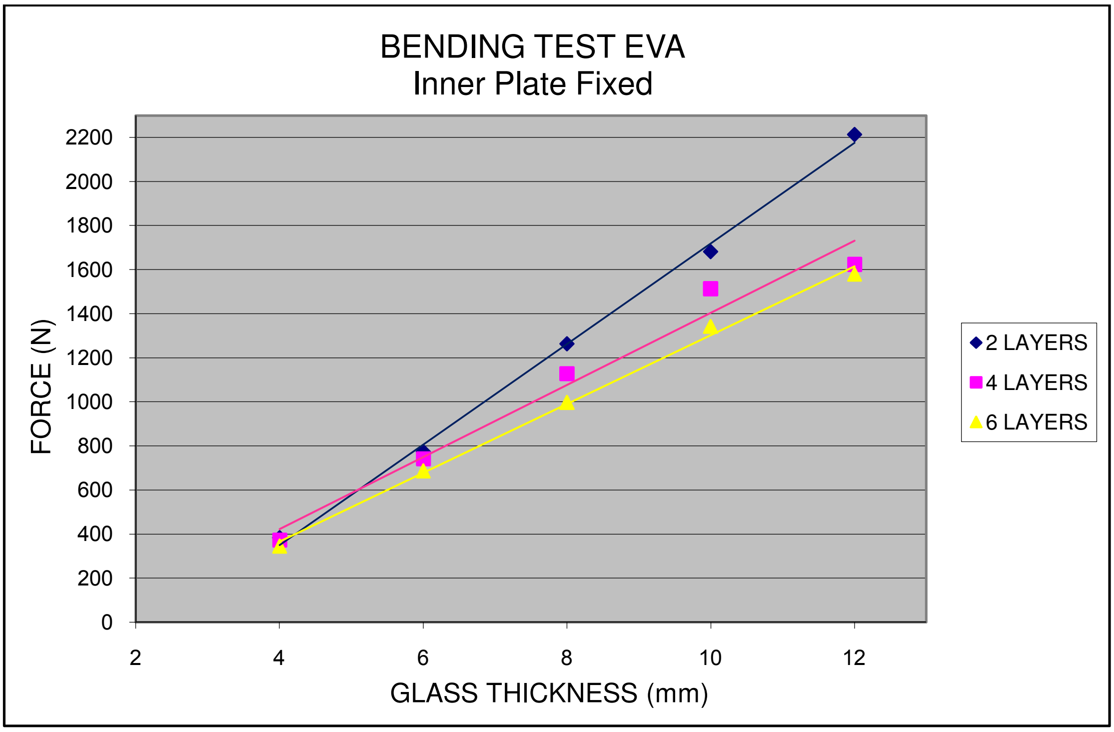

Figure (8): Testing the maximum force on (EVA) laminated glass where the thickness of inner plate was fixed and the outer plate and interlayer were changeable.

The results showed the following:

The graph shows a proportional relation the effect of changing the thickness of the glass on the maximum value of force. And in the same time the change in thickness of laminated interlayer of the glass caused a decrease in the flexural force.

Note that the results on this test were almost similar for both (EVA) and (PVB) interlayer. And this is in agreement to what was concluded by (Noville 1990) and (Quenett 1967).

Moreover, the maximum load for the glasses binded by EVA is greater than those for PVB binding material

Testing the maximum force on (PVB) laminated glass where the thickness of outer plate was fixed and the inner plate and interlayer were changeable.

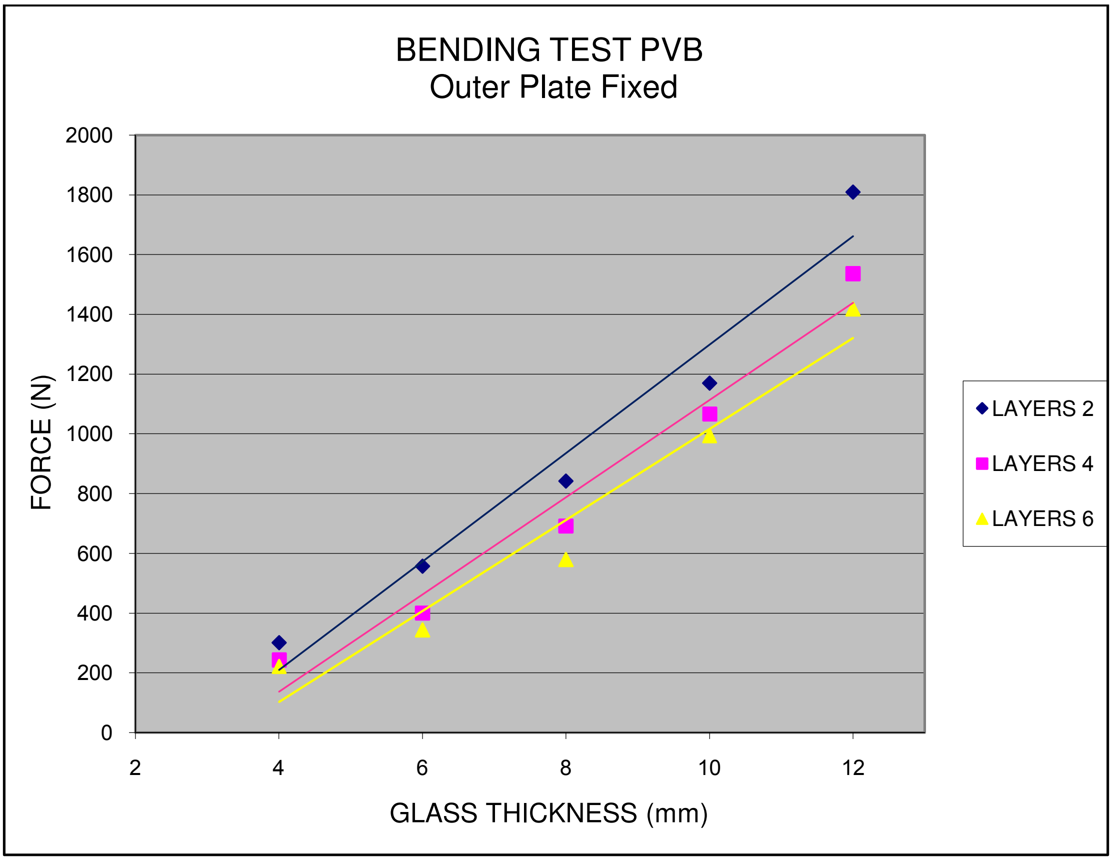

Figure (9): Testing the maximum force on (PVB) laminated glass where the thickness of outer plate was fixed and the inner plate and interlayer were changeable.

The results showed the following:

- The effect of changing the thickness of the glass on the maximum value of force. The graph above shows a proportional relation.

- The change in thickness of laminated interlayer of the glass caused a decrease in the flexural force. And this is identical to what was concluded by (Noville 1990) and (Quenett 1967).

Here is a demonstration that the change of the glass thickness from inner and outer plate does not cause a noticeable change in behavior.

Testing the maximum force on (EVA) laminated glass where the thickness of outer plate was fixed and the inner plate and interlayer were changeable.

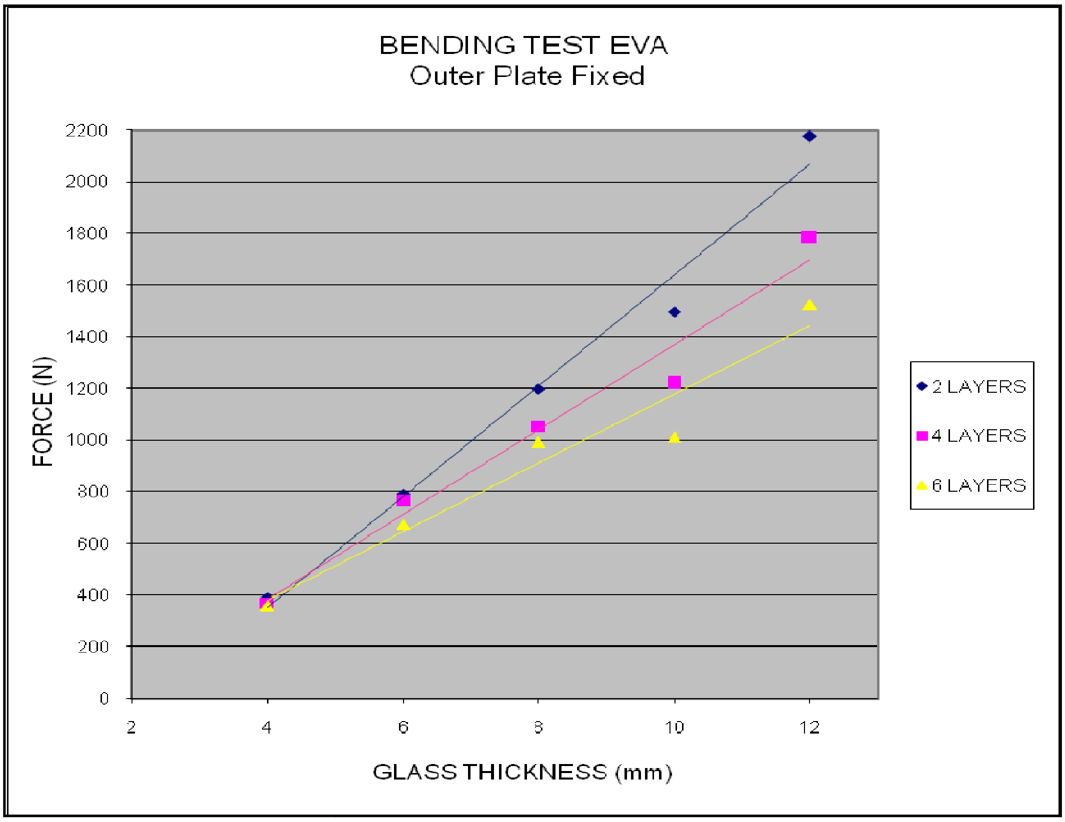

Figure (10): Testing the maximum force on (EVA) laminated glass where the thickness of outer plate was fixed and the inner plate and interlayer were changeable.

The results showed the following:

- The effect of changing the thickness of the glass on the maximum value of force. The graph shows a proportional relation.
- The change in thickness of laminated interlayer of the glass caused a decrease in the flexural force.

Here also we see that the change of thickness in inner and outer plates using either EVA or PVB as an interlayer shows almost the same behavior.

Comparison between the effects of EVA with PVB on maximum force

As the graph shows, the maximum force of EVA laminated glass is higher than the maximum force of PVB laminated glass both having the same glass thickness.

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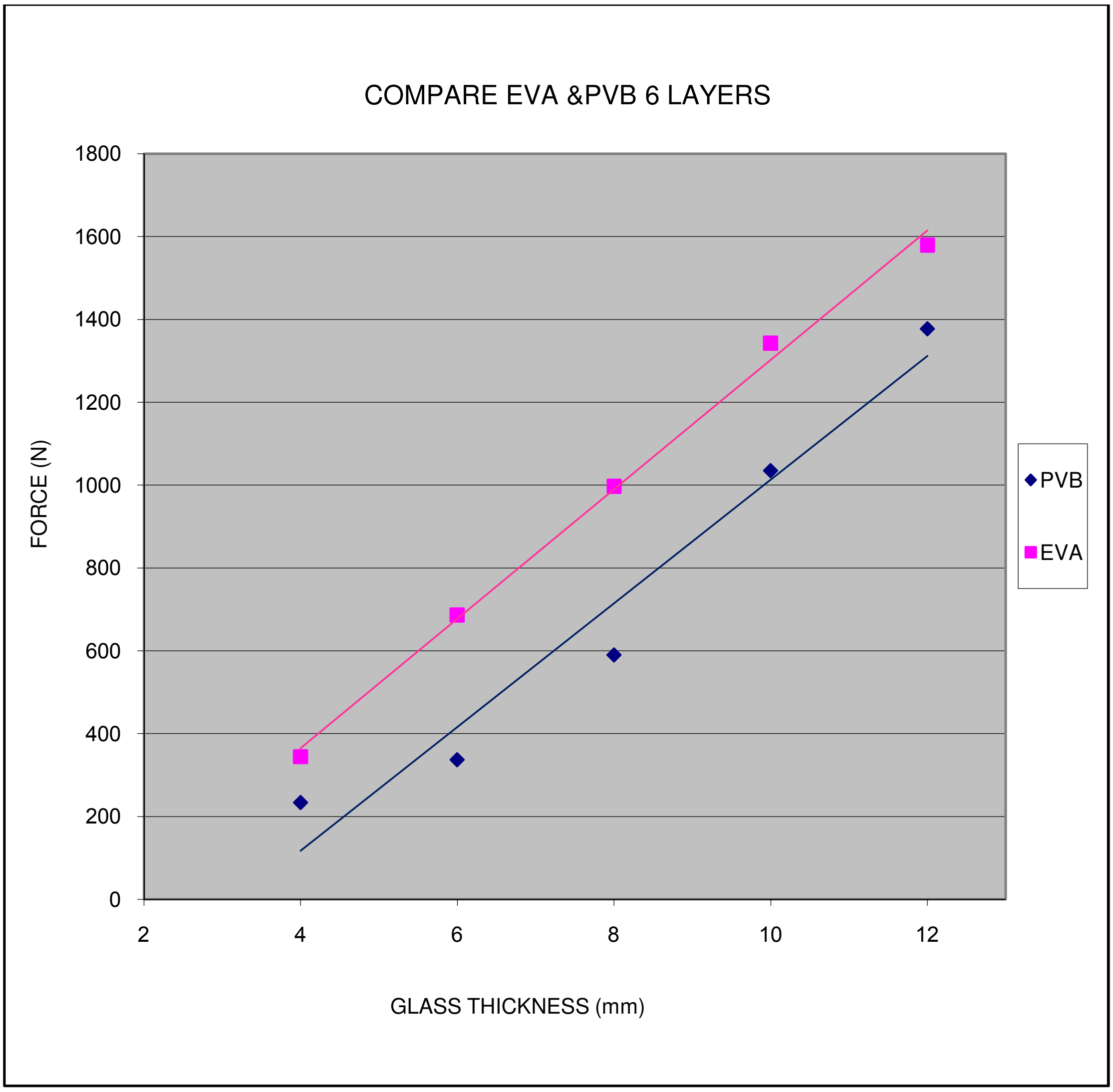

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Figure (11) Comparison between the effects of EVA with PVB on

The effect of inner and outer glass panels on maximum force using PVB.

As shown in the graph (11), when using PVB as an interlayer for the laminated glass, the effect on the value of the force that is required to break the glass does not really change when the change is on the outer plates or the inner plates both show the same glass behavior.

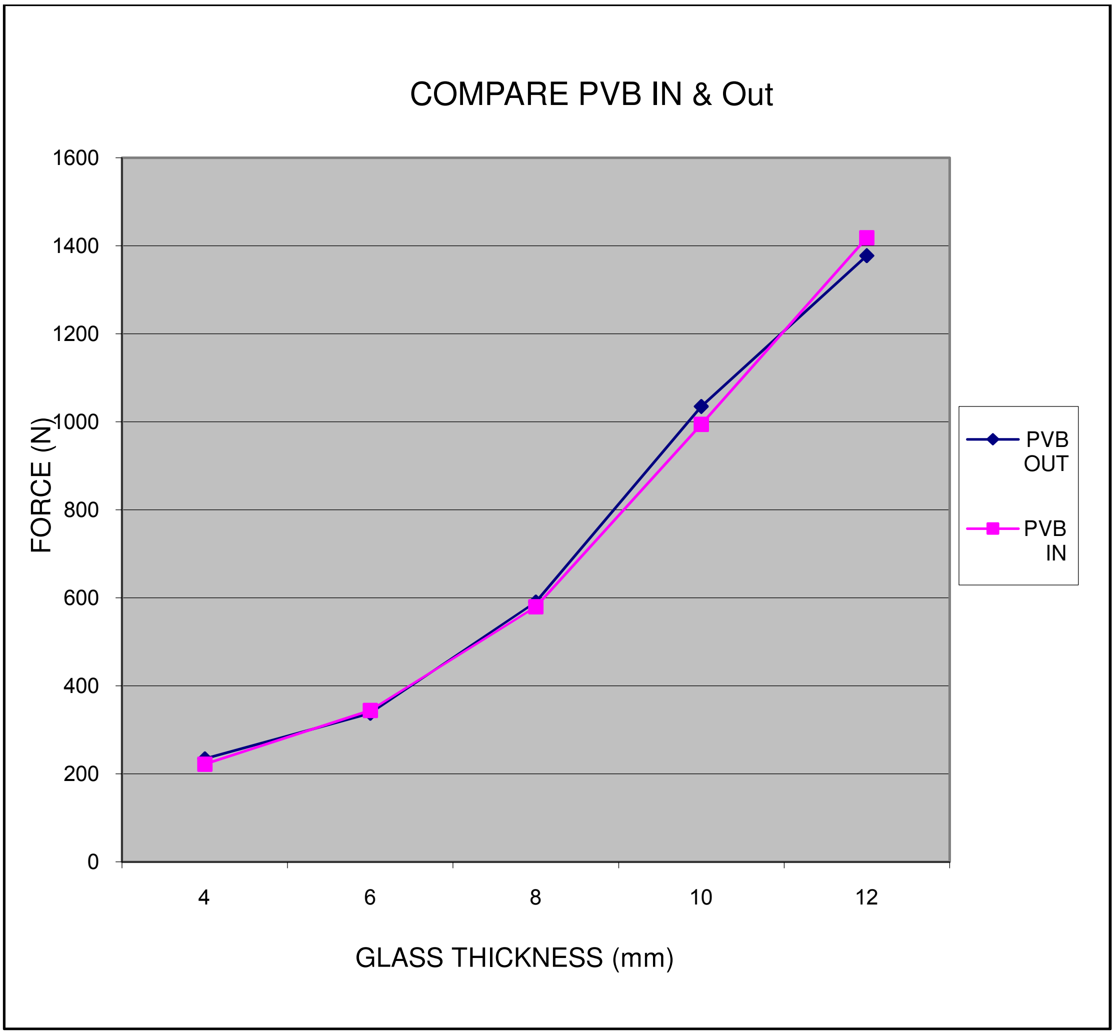

Figure (12): The effect of inner and outer glass panels on maximum force using PVB.

The effect of inner and outer glass panels on maximum force using EVA.

As mentioned previously, the graph (12) also shows that when using EVA as an interlayer for the laminated glass, the effect on the value of the force that is required to break the glass does not really change when the change is on the outer plates or the inner plates both show the same glass behavior.

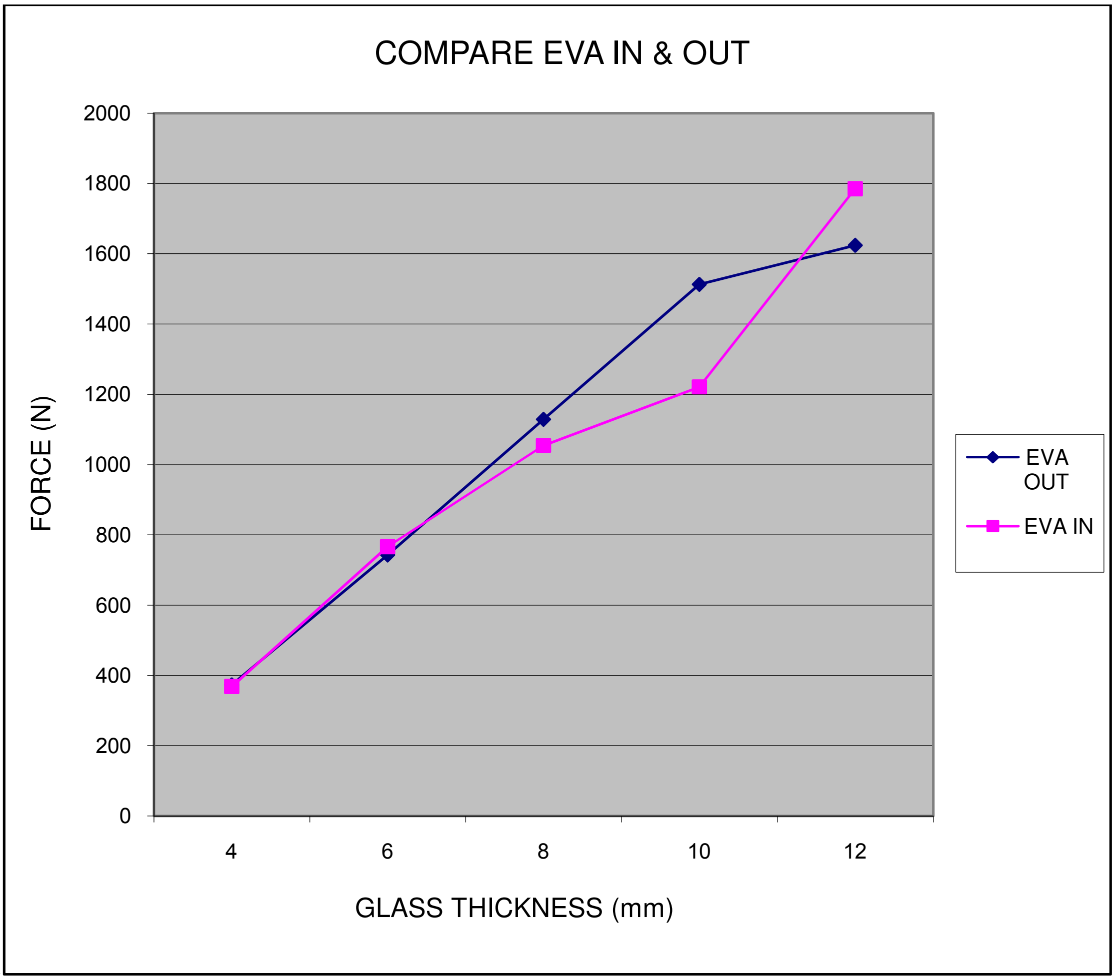

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Figure 2 The effect of inner and outer glass panels on maximum force using EVA.

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Testing the maximum force on (PVB) laminated glass where the inner glass plate was fixed, the outer glass plate thickness and the interlayer are changeable.

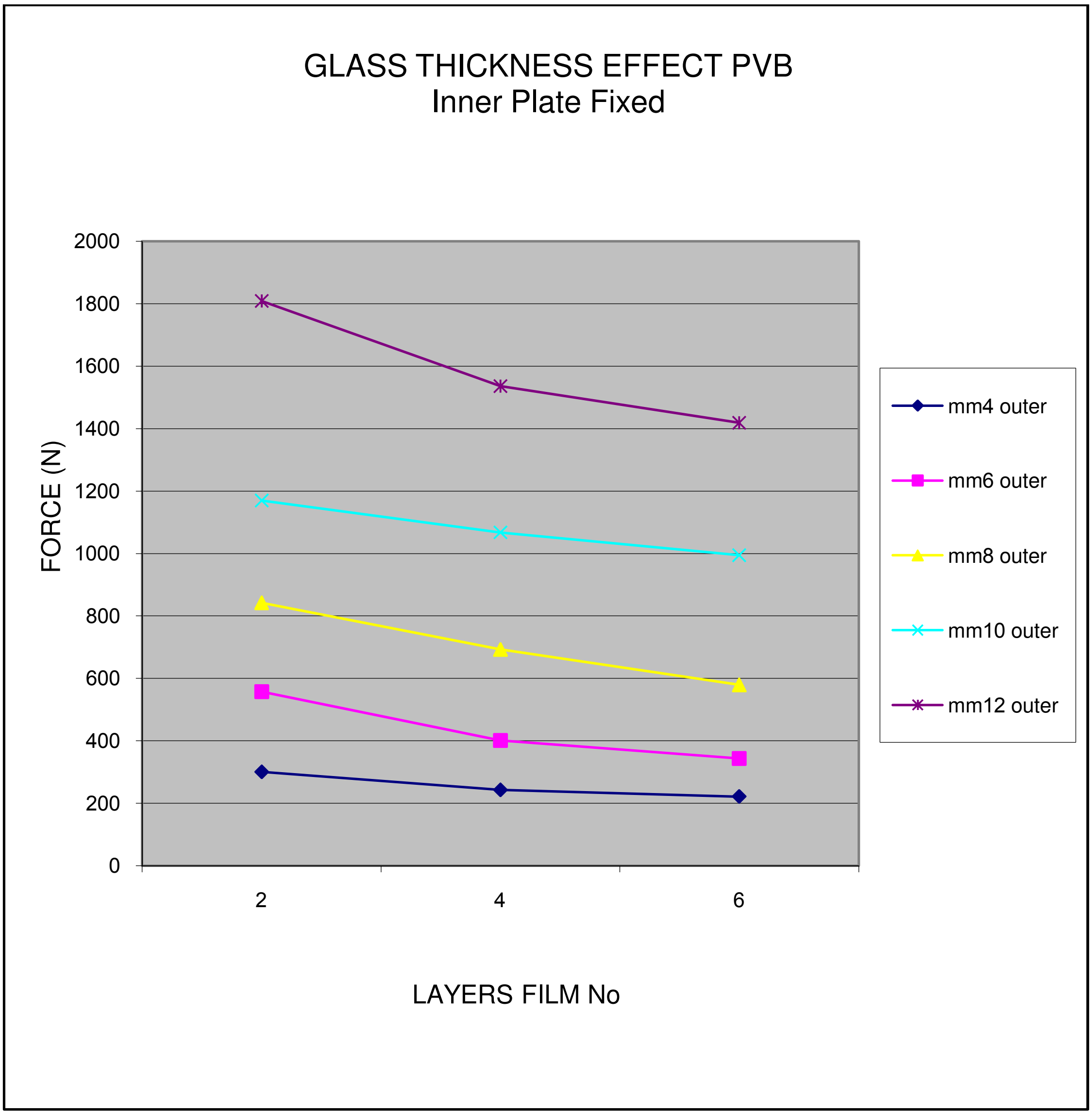

Figure (14): Testing the maximum force on (PVB) laminated glass where the inner glass plate was fixed, the outer glass plate thickness and the interlayer are changeable

The graph shows the effect of the increase of the glass thickness. As we note that the increase in glass thickness cause an increase in glass strength to bending force. While the opposite effect for interlayer thickness.

Testing the maximum force on (EVA) laminated glass where the inner glass plate was fixed; the outer glass plate thickness and the interlayer are changeable.

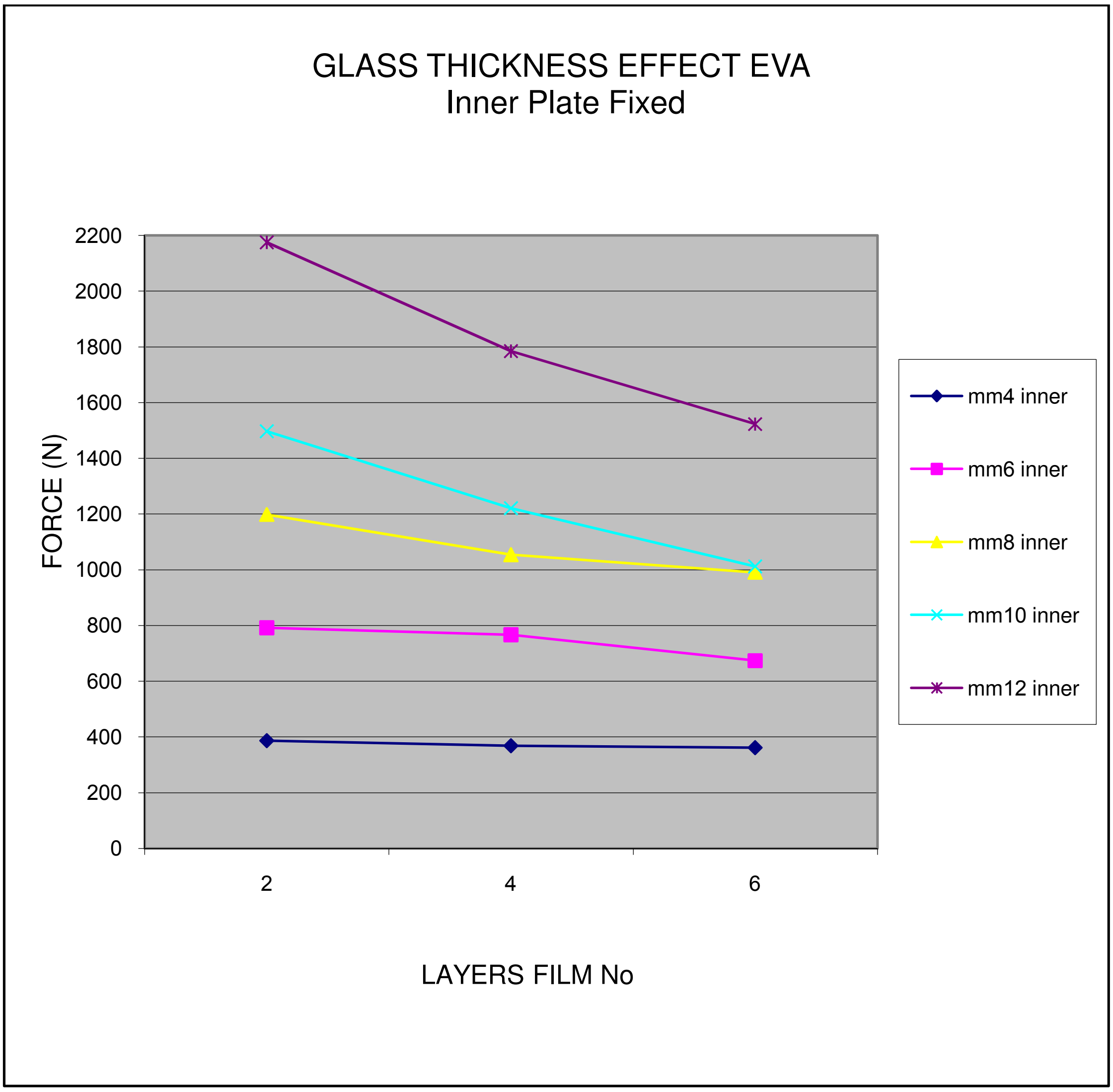

Figure (15): Testing the maximum force on (PVB) laminated glass where the inner glass plate was fixed, the outer glass plate thickness and the interlayer are changeable

The graph shows the effect of the increase of the glass thickness. As we note that the increase glass thickness causes an increase in glass strength.

Also this shows that the PVB and EVA interlayer have the same behavior during this test.

Testing the maximum force on (PVB) laminated glass where the outer glass plate was fixed; the inner glass plate thickness and the interlayer are changeable.

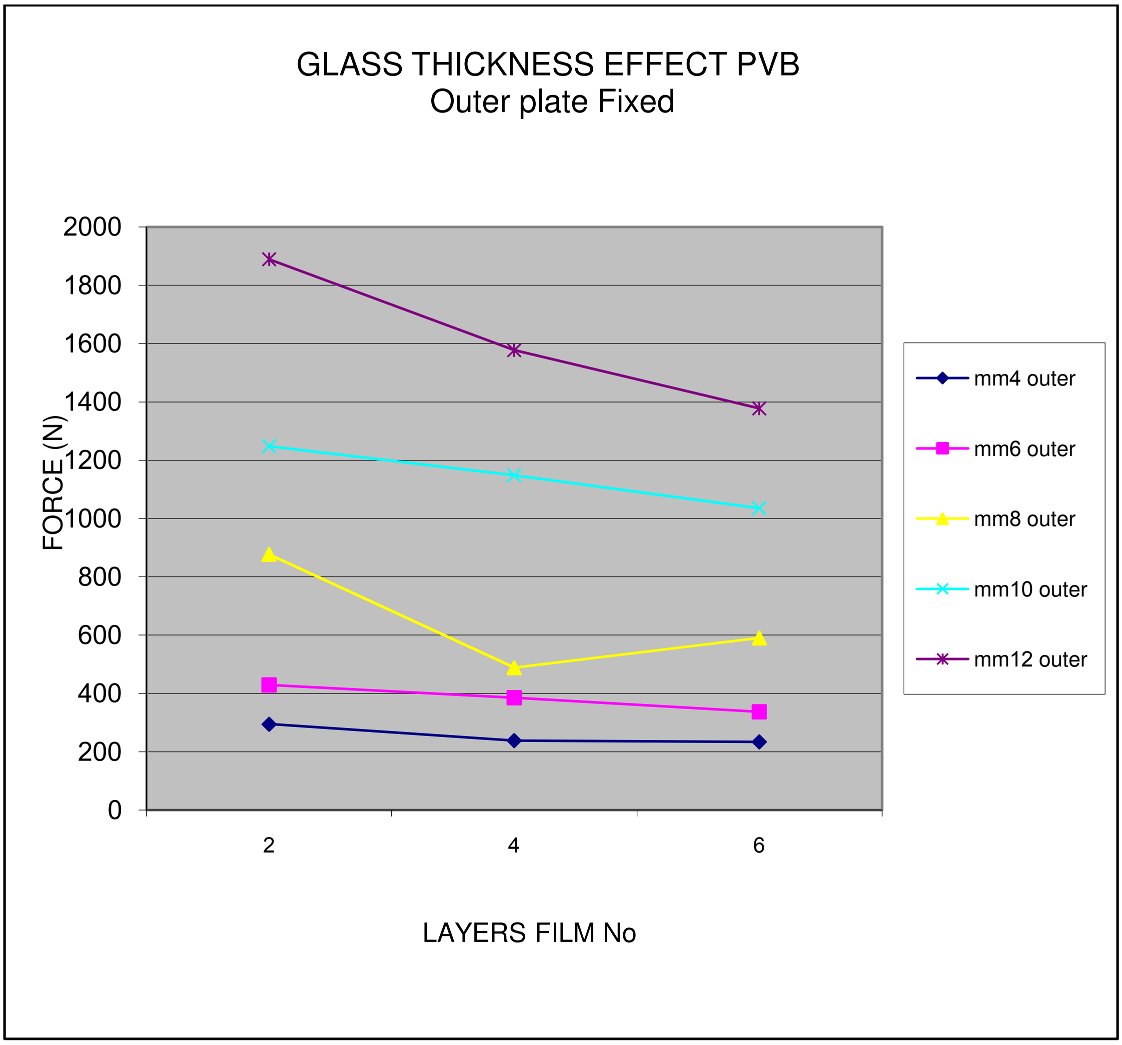

Figure (16) Testing the maximum force on (PVB) laminated glass where the outer glass plate was fixed; the inner glass plate thickness and the interlayer are changeable.

The graph shows the effect of the increase of the glass thickness. As we note that the increase glass thickness causes an increase in glass strength. While the opposite effect for interlayer thickness.

This also shows that the change of the outer or the inner glass plate thickness gives the same effect on glass strength.

Testing the maximum force on (EVA) laminated glass where the outer glass plate was fixed; the inner glass plate thickness and the interlayer are changeable.

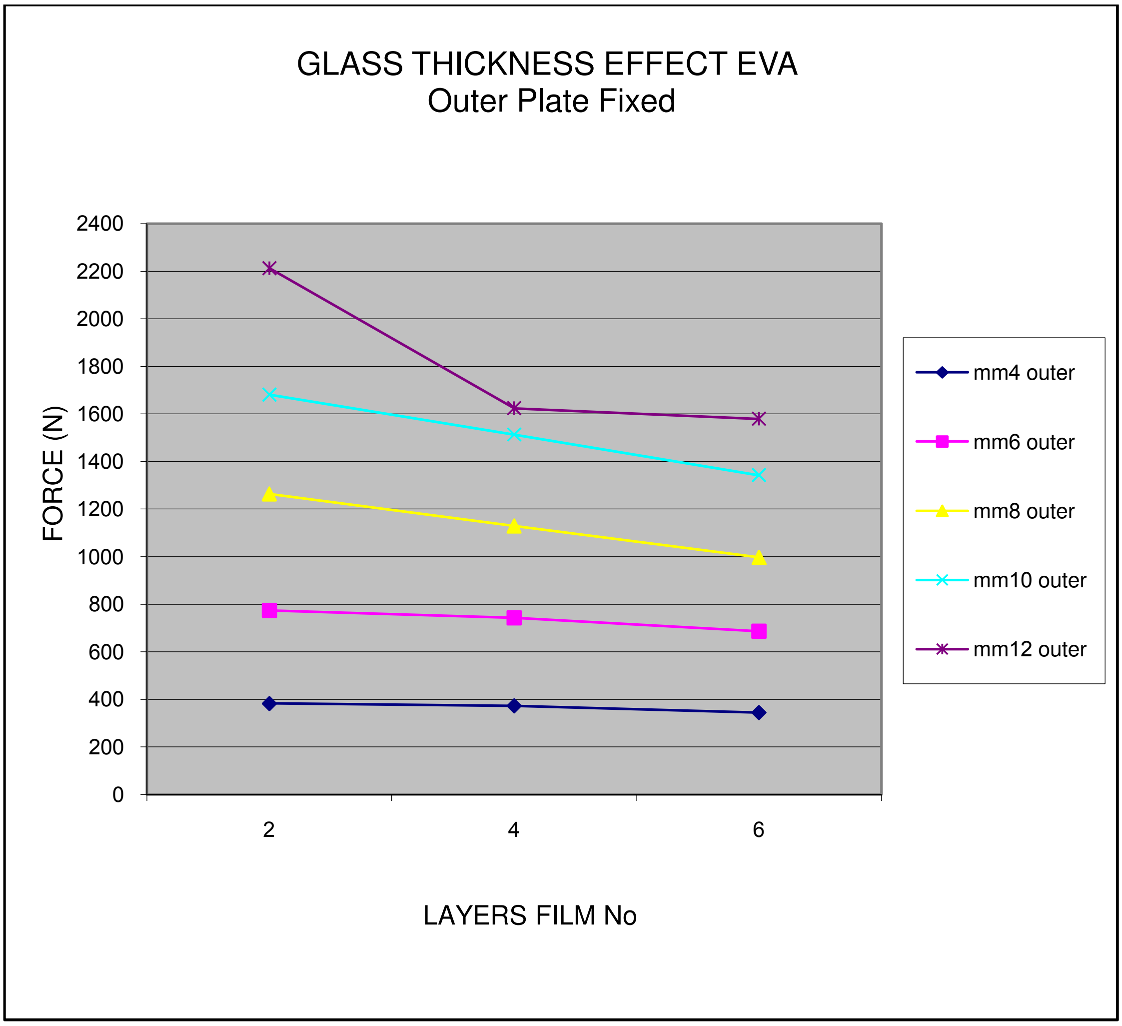

Figure (17) Testing the maximum force on (EVA) laminated glass where the outer glass plate was fixed; the inner glass plate thickness and the interlayer are changeable.

The graph shows the effect of the increase of the glass thickness. As we note that the increase glass thickness causes an increase in glass strength.

This also shows that either in PVB or EVA interlayers the change of the outer or the inner glass plate thickness gives the same effect on glass strength.

Testing the maximum deflection on (PVB) laminated glass where the inner glass plate was fixed and the outer glass the interlayer was changeable.

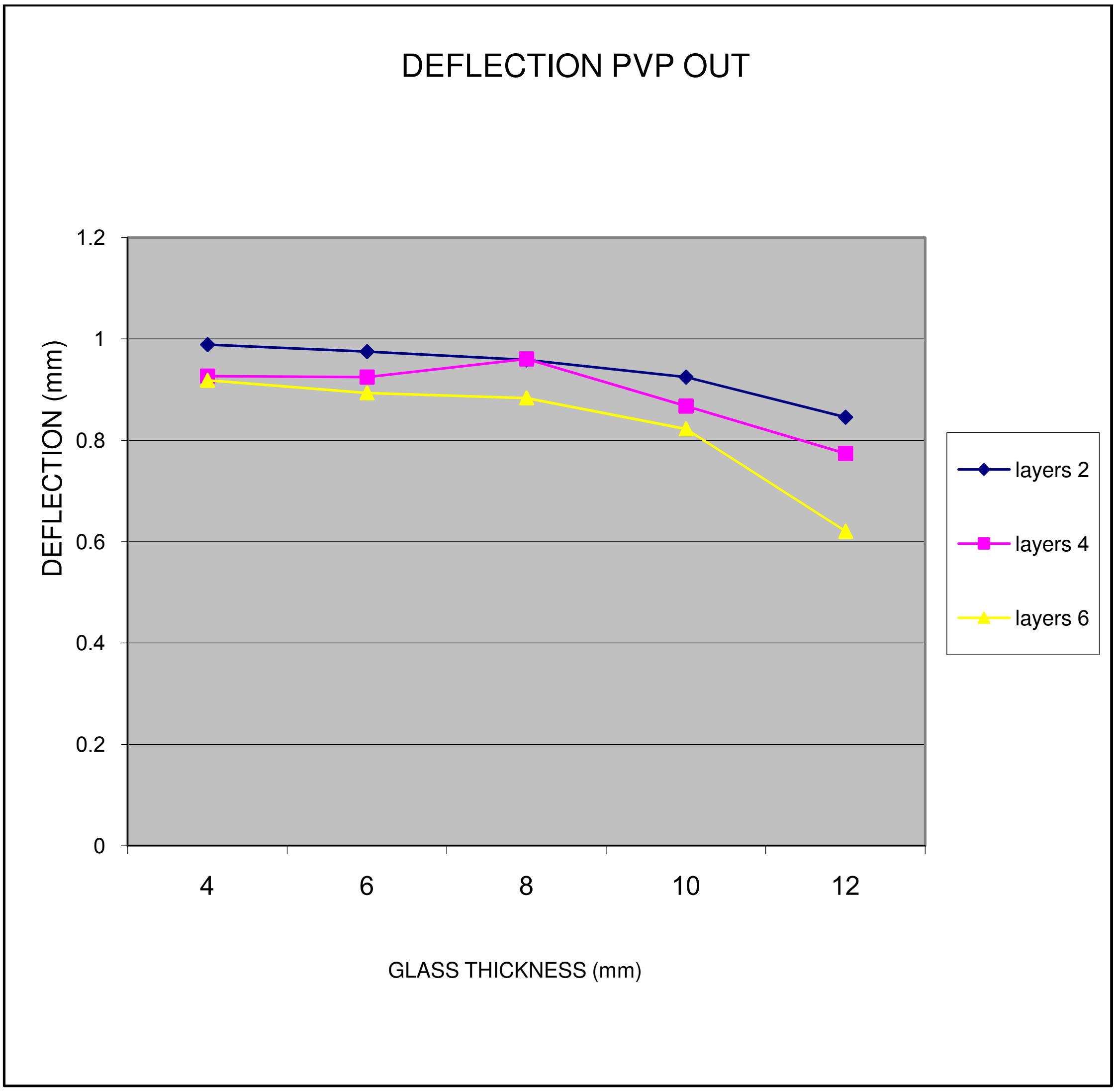

Figure (18): Testing the maximum deflection on (PVB) laminated glass where the inner glass plate was fixed and the outer glass the interlayer was changeable.

As shown in the graph, when increasing the number of interlayer (PVB), the test showed that the glass resistance for fracture is less and the deflection before the actual fracture happens has also decreased.

Testing the maximum deflection on (EVA) laminated glass where the inner glass plate was fixed, the outer glass and the interlayer was changeable.

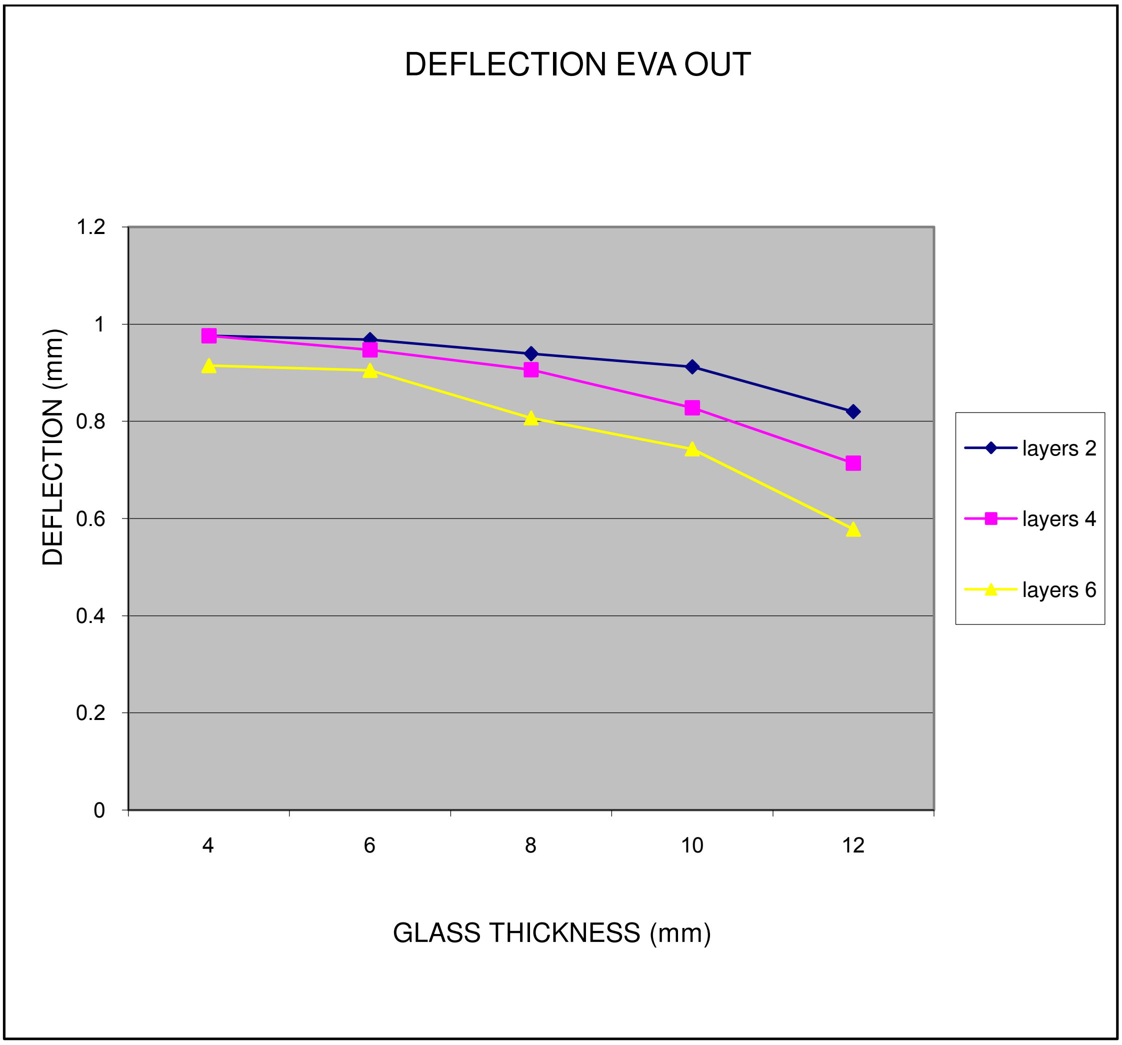

Figure (19) Testing the maximum deflection on (EVA) laminated glass where the inner glass plate was fixed and the outer glass the interlayer was changeable.

As shown above in the graph, when increasing the number of interlayer (EVA), the test showed that the glass resistance for fracture is less and the deflection before the actual fracture happens has also decreased.

PVB and EVA interlayer showed same behavior in this test as the results showed previously.

Testing the maximum deflection on (PVB) laminated glass where the outer glass plate was fixed, the inner glass and interlayer was changeable.

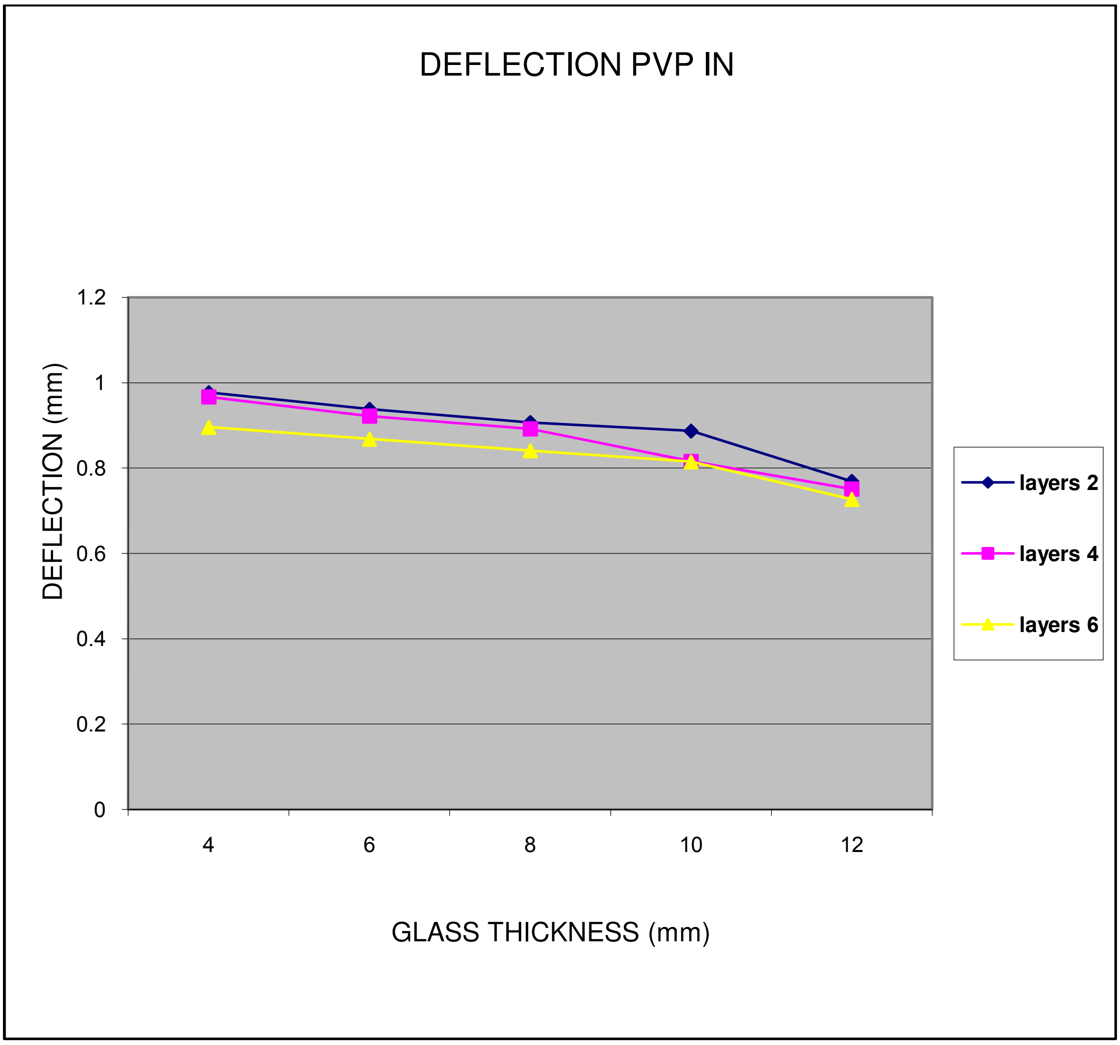

Figure (20): Testing the maximum deflection on (PVB) laminated glass where the outer glass plate was fixed, the inner glass and interlayer was changeable.

As shown in the graph, when increasing the number of interlayer (PVB), the test showed that the glass resistance for fracture is less and the deflection before the actual fracture happens has also decreased.

Changing the inner or the outer glass plate thickness as the results showed has almost the same effect.

Testing the maximum deflection on (EVA) laminated glass where the outer glass plate was fixed, the inner glass and interlayer was changeable.

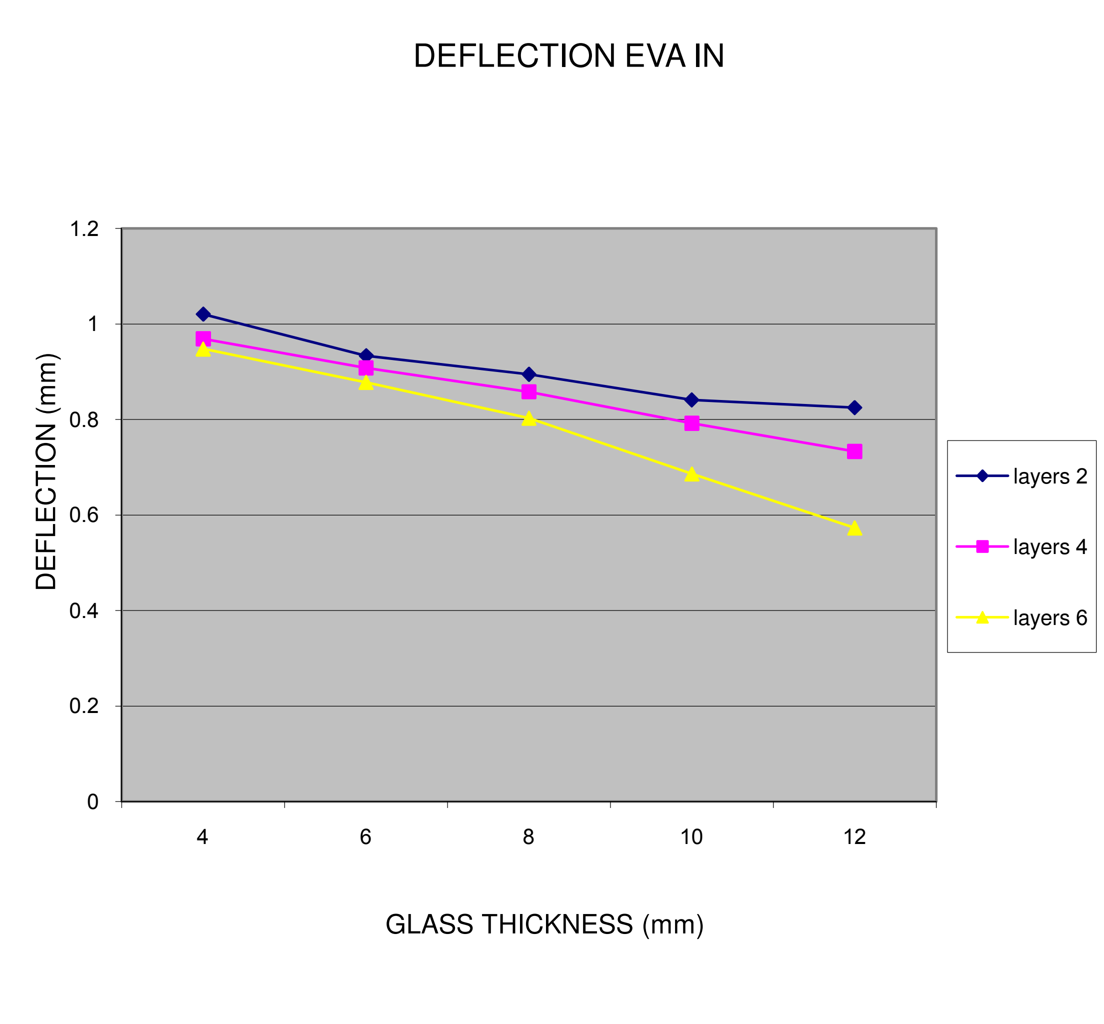

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Figure (21): Testing the maximum deflection on (EVA) laminated glass where the outer glass plate was fixed, the inner glass and interlayer was changeable.

As shown in the ` the number of interlayer (EVA), the test showed that the glass resistance for fracture is less and the deflection before the actual fracture happens has also decreased.

The test proved that the changing of the glass thickness (inner or outer plates) cause increase in glass strength and the increase in number of interlayers (EVA or PVB) cause to reduce the deflection on the glass before the fracture happen.

Samples after bending fracture

The failure was spread throughout the glass as presented below in the figure (22).

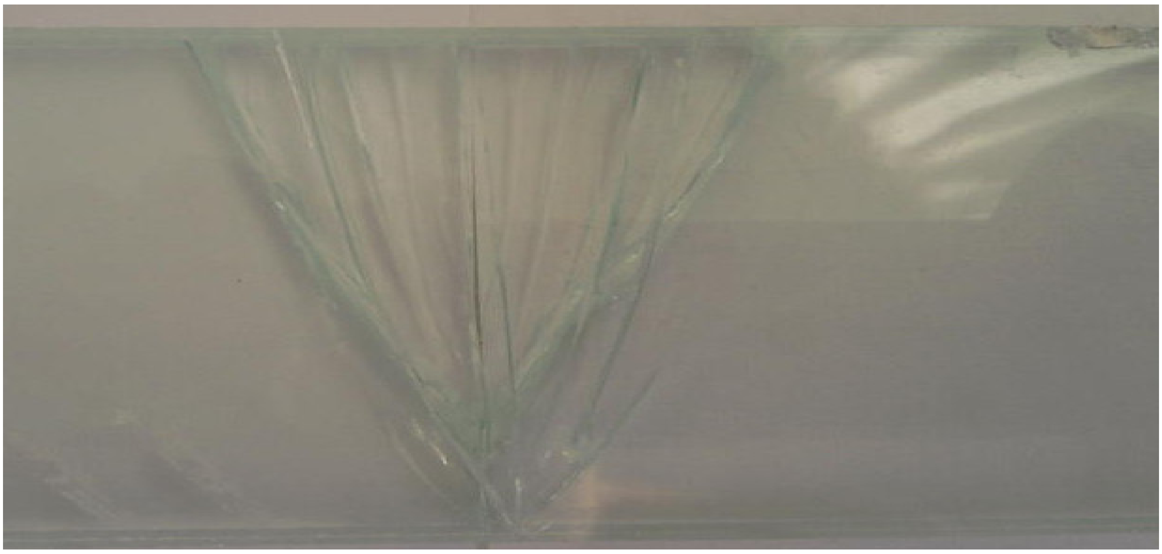

Figure (22): Testing sample after point bend test (top view).

As shown the failure was linear in the inner and outer glass, and it was not on the same alignment. And the failure was nonlinear in the interlayer figure (23).

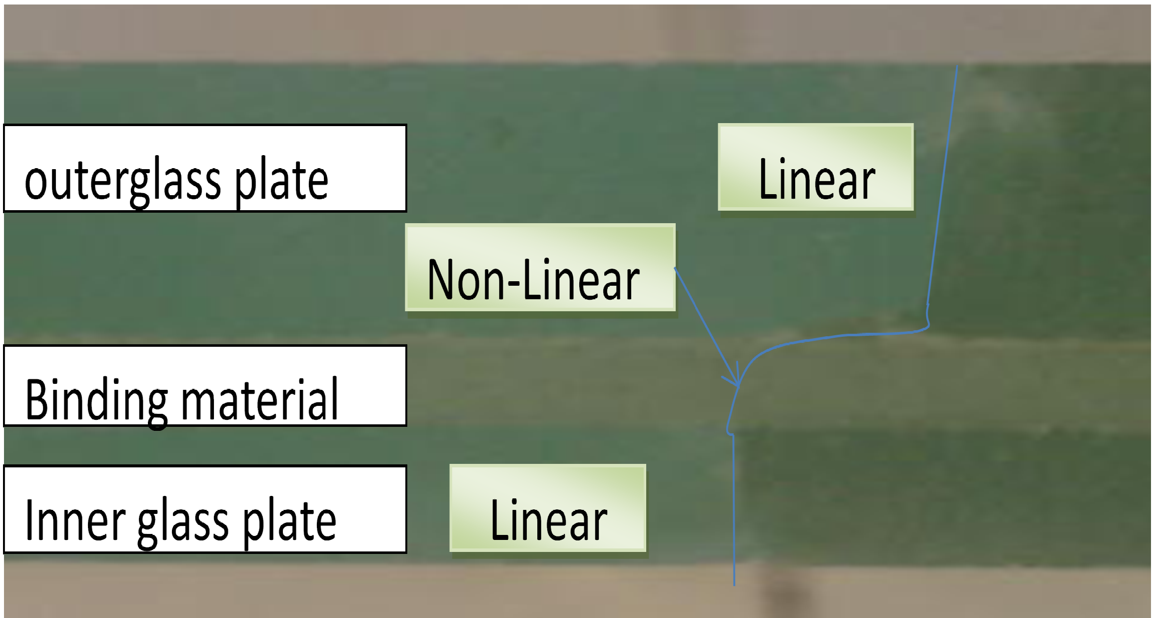

Figure (23): Testing sample after point bend test (side view).

5.2 Charpy Testing Results and Discussion

Test for the absorbed energy for (PVB) laminated glass.

The graph (24) shows that the absorbed energy increases with the increase of the number of interlayer. Also it shows a proportional relation between the glass thickness and the absorbed energy. And this is identical to what was concluded by (Keller 2005).

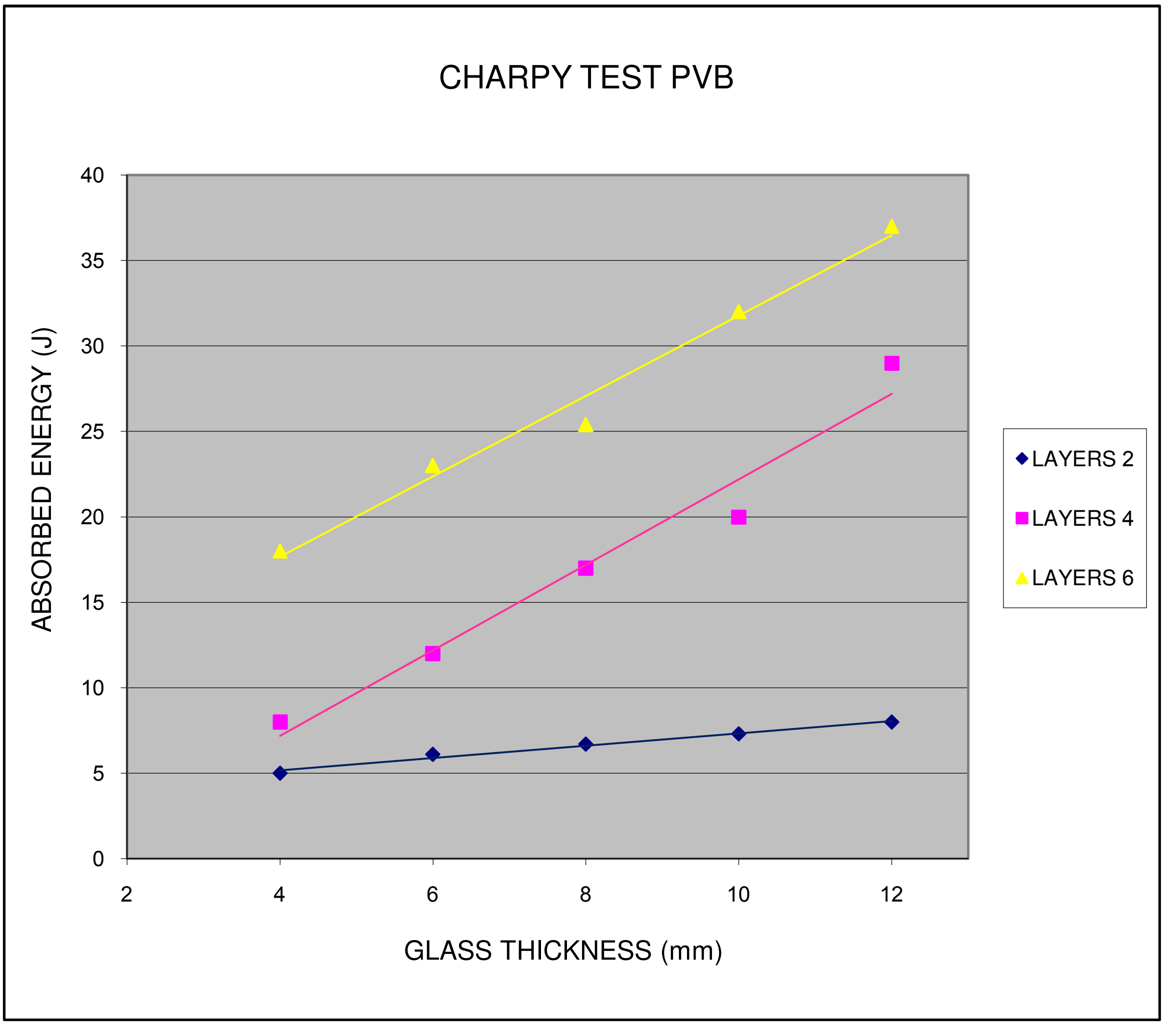

Figure (24)Test for the absorbed energy for (PVB) laminated glass.

Test for the absorbed energy for (EVA) laminated glass.

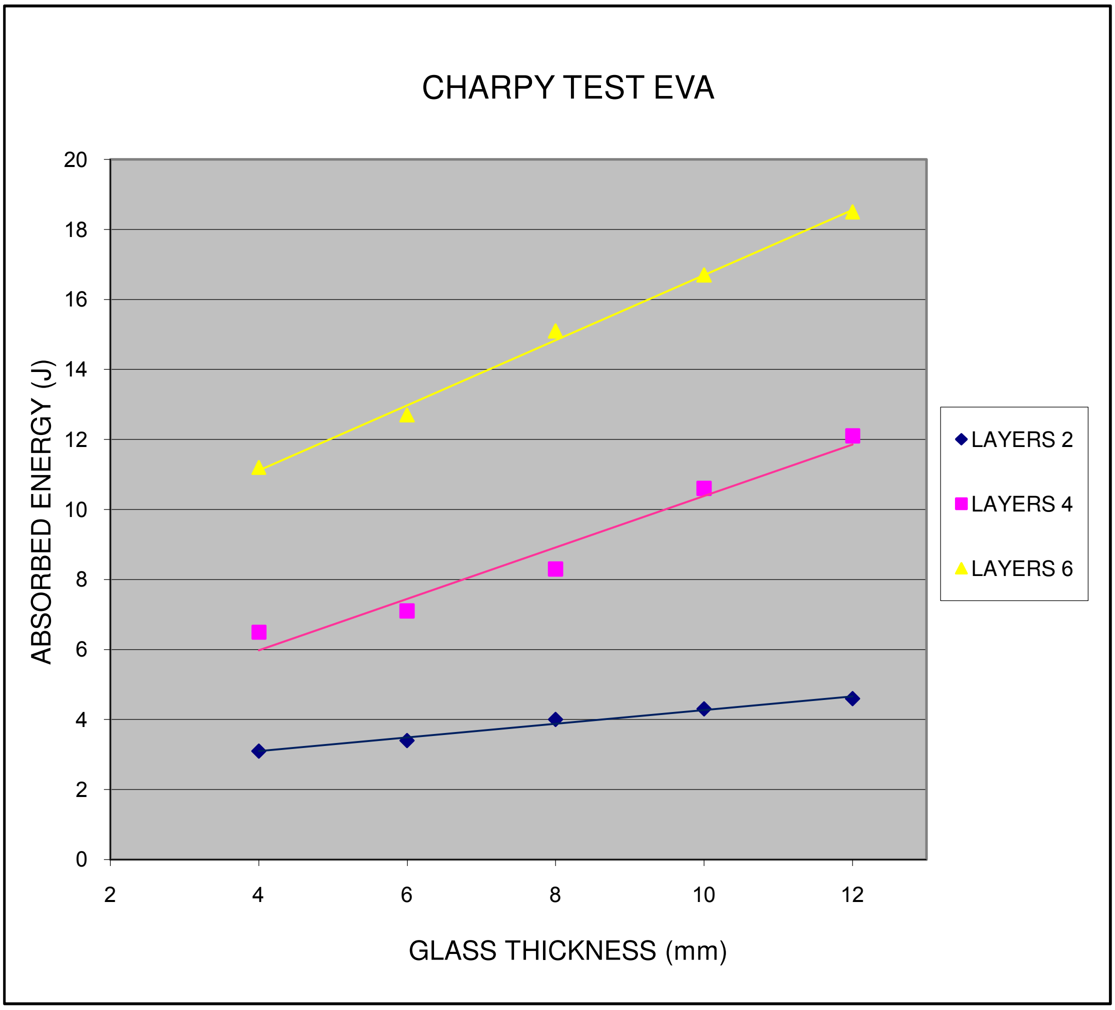

Figure (25): Test for the absorbed energy for (EVA) laminated glass.

Also here the graph shows a very similar behavior for the EVA laminated glass where the absorbed energy increases with the increase of the number of interlayers. Also it shows a proportional relation between the glass thickness and the absorbed energy. And this is to what was concluded by (Keller 2005).

Charpy test comparison

Comparison between the effect (absorbed energy) of EVA interlayer and PVB interlayer (two layers).

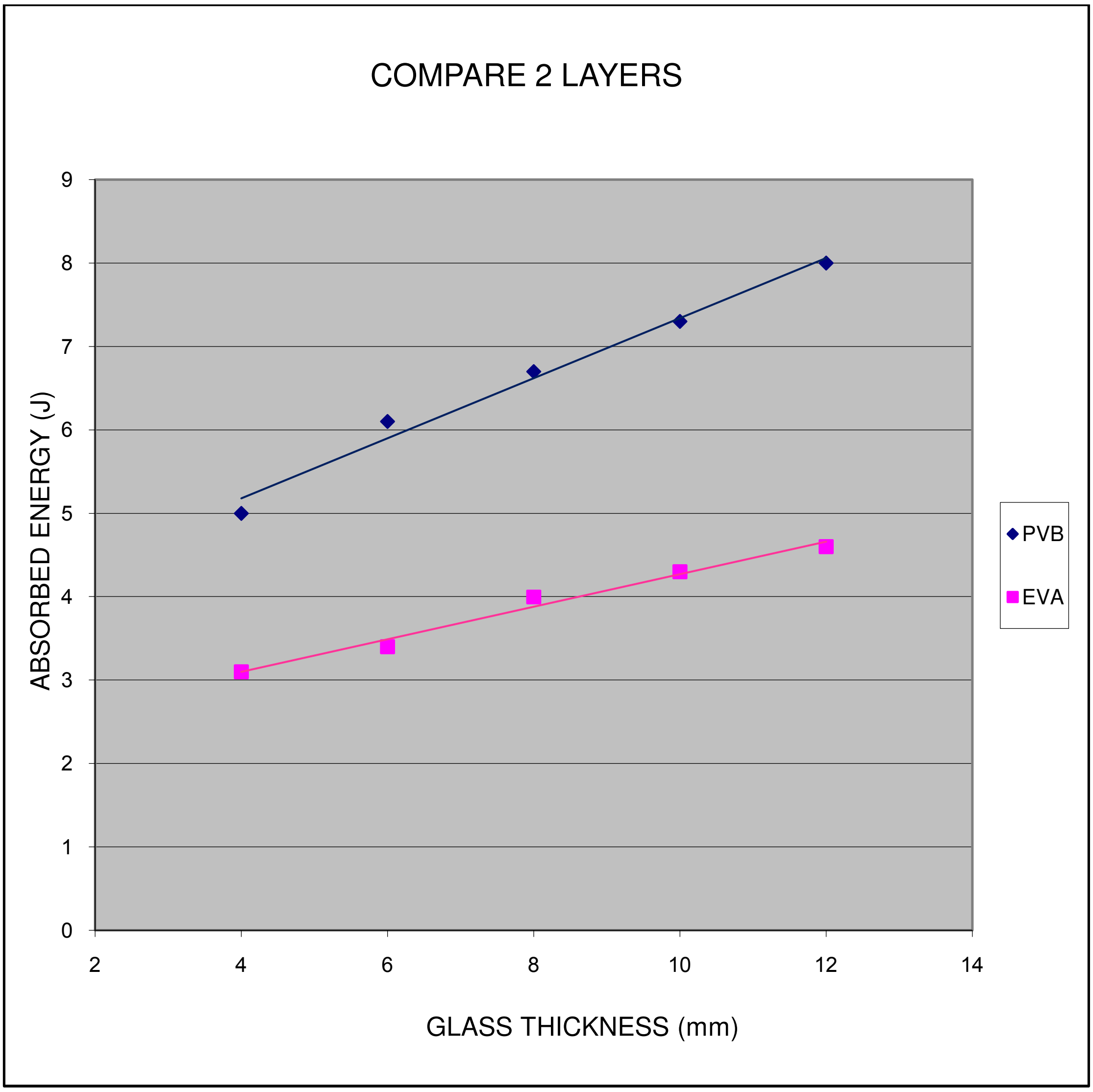

Figure (26): Comparison between the effect (absorbed energy) of EVA interlayer and PVB interlayer (two layers).

The test results show a clear indication the absorbed energy is more when using PVB interlayer. As we see in the graph above the rate of absorbed energy was between (5 - 8) J using PVB while using EVA it is between (3-4.5) J.

Comparison between the effect (absorbed energy) of EVA interlayer and PVB interlayer (four layers).

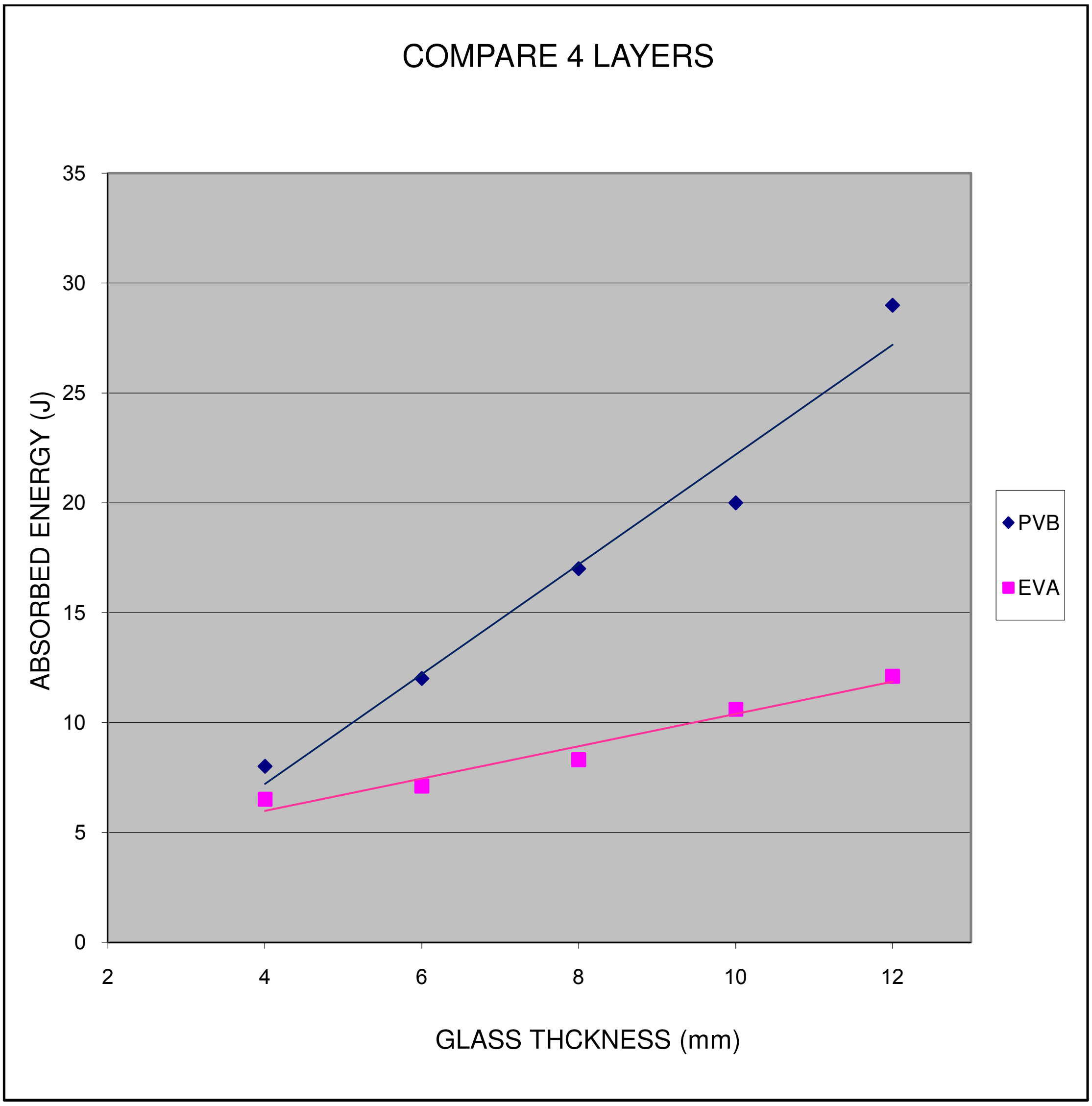

Figure (3) Comparison between the effect (absorbed energy) of EVA interlayer and PVB interlayer (four layers).

The graph shows also the same result as before. Note that the impact on the absorbed energy was significantly increased when using four layers.

Comparison between the effect (absorbed energy) of EVA interlayer and PVB interlayer (six layers).

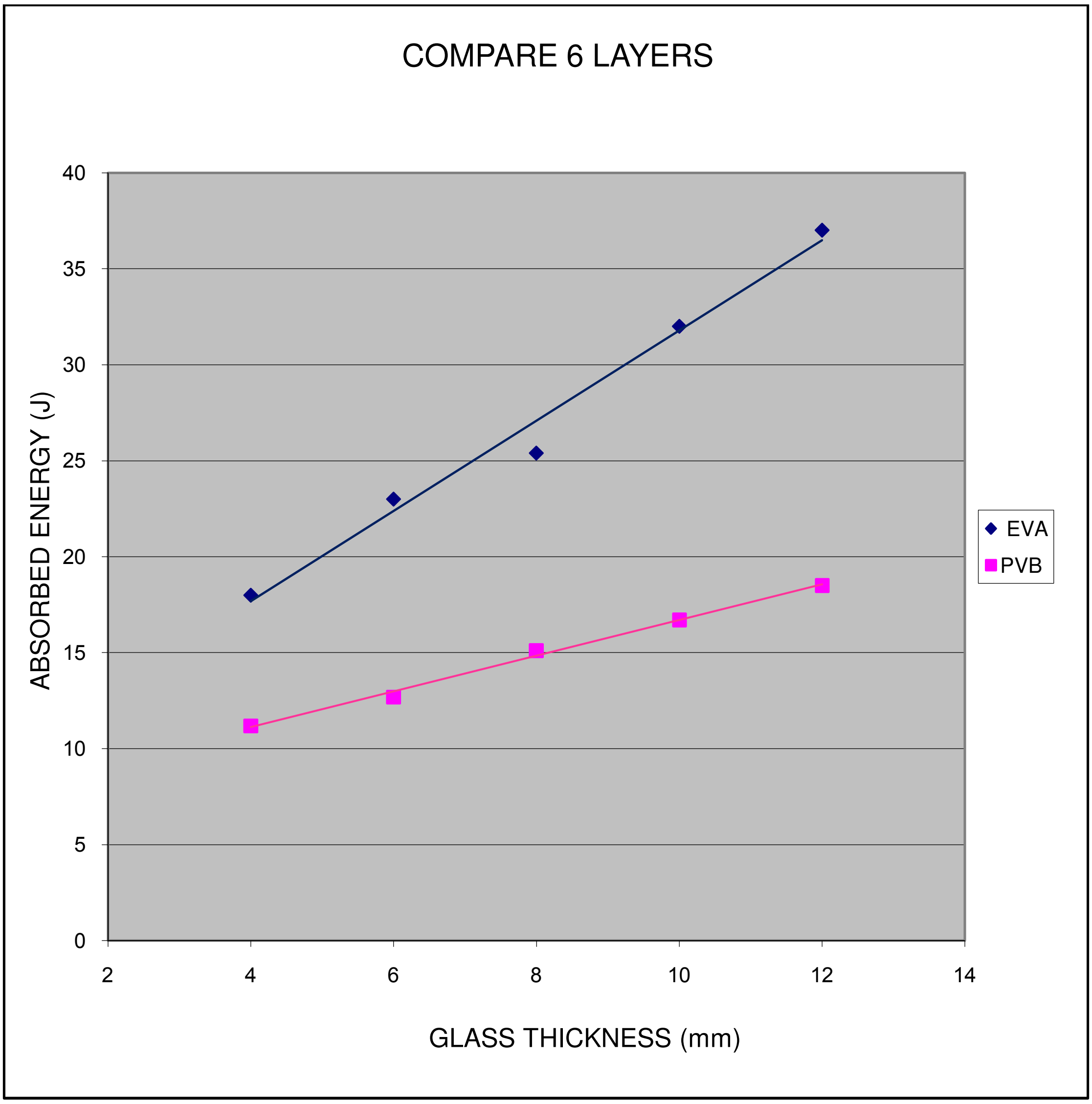

Figure 4 Comparison between the effect (absorbed energy) of EVA interlayer and PVB interlayer (six layers).

The same previous result to confirm the great impact of laminated interlayer thickness on the absorbed energy, where the greater the number of layers of laminated interlayer will increase the amount of the absorbed energy.

Samples after the fracture

As shown in figure (29), when the Charpy test was applied for the purpose of testing the absorbed energy, the result was that the sample was broken into two separate pieces which shows the increase in the absorbed energy and the complete penetration.

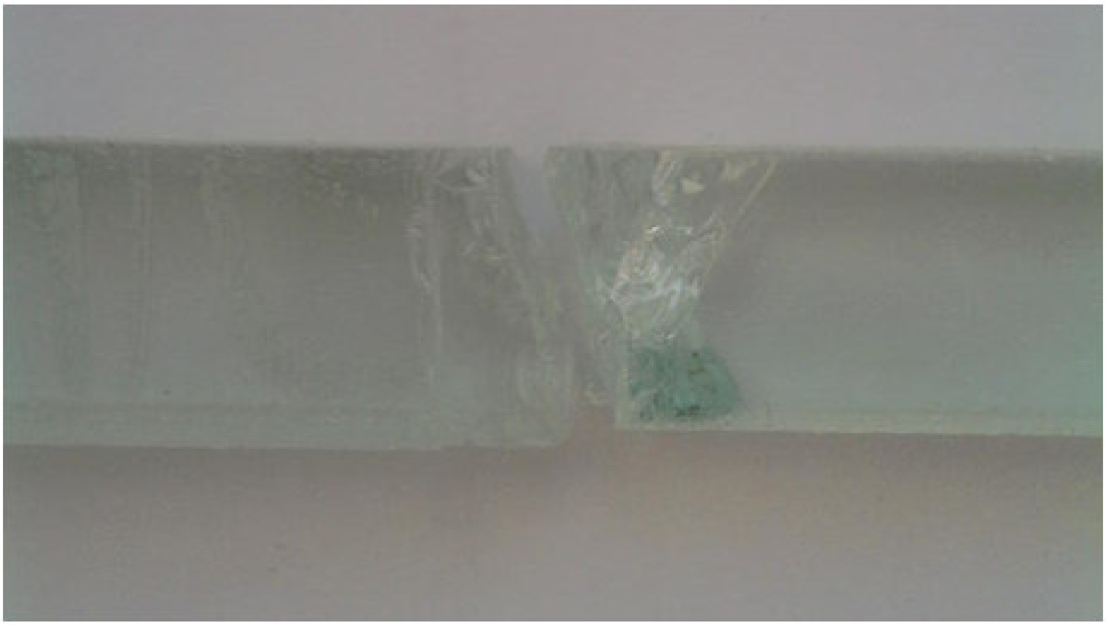

Figure (5) Testing sample after Charpy test.

As shown in the picture. A completed fracture was occurred to both glass panes and the interlayer material .this means that the measured absorbed energy was been tested to make perfect penetration.

5.3 Maximum force and absorbed energy modeling.

The modeling has been done to develop equations that can be used for determining the maximum force for the fracture of the glass depending on the glass thickness and the numbers of interlayer . This mainly can be used in the calculation of high rise building and penetration resistance in private and local housings.

Regression analysis is a statistical tool for the investigation of relationships between variables glass plate thickness and interlayer thickness. Usually, the investigator seeks to ascertain the causal effect of one variable upon another. This investigation assembles data on the underlying variables of interest and employs regression to estimate the quantitative effect of the causal variables upon the variable that they influence.

To study the relationship between the maximum bending force and both of glass thickness and interlayer number and the same thing for maximum absorbed energy the multiple linear regression was be used. Which is a linear regression model with one dependent variable (the maximum bending force or maximum absorbed energy) and more than one independent variables (glass thickness and interlayer number). The multiple linear regression assumes that the response variable is a linear function of the model parameters and there are more than one independent variables in the model.

The developed model may be written:

$Y = \alpha + \beta x_1 + \gamma x_2 + \varepsilon$ ....[1]

where

Y : is dependent variable (Max bending force or Max absorbed energy),

α, β, γ : are regression coefficients,

x_1 ,x_2; are independent variables(glass thickness and interlayer numbers).

ε : a random error .

All results process and analysis in Minitab software to find the regression equations that can be used to find the best laminated glass thickness and interlayer to resist external force depending on application.

The Maximum Force Modeling

MAX FORCE PVB = - 348 + 174 x_1 - 58.3 x_2

S = 157.443 R-Sq = 92.7% R-Sq(adj) = 91.5%

MAX FORCE EVA = - 88 + 185 x_1 - 68.3 x_2

S = 130.899 R-Sq = 95.4% R-Sq(adj) = 94.7%

where

* x_1 Glass plate thickness (mm)

* x_2 Interlayer thicknesses (mm)

* S Sum of squares

* R-Sq R-squared (is the ratio of the regression sum of squares to the total sum of squares)

*R-Sq(adj) Adjusted R-squared

The Maximum Absorbed Energy Modeling

The regression equations are

ABSORBED ENERGY FOR PVB = - 17.4 + 5.12 x_2 + 1.74 x_3

S = 3.25427 R-Sq = 91.7% R-Sq(adj) = 90.3%

ABSORBED ENERGY FOR EVA = - 6.71 + 2.74 x_2 + 0.620 x_3

S = 1.05299 R-Sq = 96.3% R-Sq(adj) = 95.7%

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Where

* x_2 Interlayer thicknesses (mm)

* x_3 Glass plate thickness (mm)

* S Sum of squares

* R-Sq R-squared

*R-Sq(adj) Adjusted R-squared

CHAPTER SIX: CONCLUSION AND FUTURE WORK

6.1 Conclusion

1. The higher the thickness (number) of interlayer, the less the maximum load capacity of the laminated glass bonded with PVB material for fixed thickness of the inner plate.
2. The higher the thickness (number) of interlayer, the less the maximum load capacity of the laminated glass bonded with EVA material for fixed thickness of the inner plate.
3. The position of the plate of the fixed thickness dose not affect the maximum load capacity and maximum load capacity for laminated glass bonded with EVA is greater than that for the ones bonded with PVB provided that the same conditions are maintained.
4. The higher the thickness of bonded (number) interlayer, the higher the amount of the absorbed energy. Moreover , the laminated glass which is bonded with PVB absorbed more energy than those bonded with EVA.
5. Regression models were developed to calculate the maximum load capacity and amount of absorbed energy separately depending on the thickness of glass and the thickness of bonding interlayer regardless the position of glass plates
6. The propagation of fracture was linear within the glass plate and non linear within the bonding polymer.

6.2 Future Work

In order to reach to the optimal structure of the glass, a lot of variables are to be considered, tried out, reported then studied and according to it, structure of the glass will depend on the behavior and specification needed for a particular application.

Examples of these variables that can affect the behavior of the glass and deserve to be studied further more:

- Adding to previous experiments Size variation will provide us with more information on the behavior difference for the glass in cases of size changing.
- Applying previous experiments on tempered glass and studying the data resulted from them as done previously.

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APPENDIX A RESULTS TABLES

Table 1 Test samples For Bending Test (PVB)
The outer plates and interlayer thickness changeable)

Test samples For Bending Test (PVB) IN				PVB	PVB
Sample No	outer glass thickness(mm)	interlayer No	Inner glass thickness(mm)	Max Force (N)	Max Disp (mm)
1	4	2	4	295.0	0.989
2	4	4	4	238.1	0.927
3	4	6	4	233.8	0.919
4	6	2	4	429.4	0.975
5	6	4	4	385.7	0.925
6	6	6	4	337.3	0.894
7	8	2	4	877.5	0.959
8	8	4	4	488.1	0.961
9	8	6	4	590.0	0.884
10	10	2	4	1248.1	0.925
11	10	4	4	1148.0	0.868
12	10	6	4	1035.0	0.823
13	12	2	4	1889.4	0.846
14	12	4	4	1576.9	0.774
15	12	6	4	1377.5	0.621

Table 2 Test samples For Bending Test (PVB)
(The inner plates and interlayer thickness changeable)

Test samples For Bending Test (PVB) OUT				PVB	PVB
Sample No	outer glass thickness	interlayer No	Inner glass thickness	Max Force (N)	Max Disp (mm)
1	4	2	4	301.4	0.977
2	4	4	4	243.4	0.967
3	4	6	4	221.7	0.896
4	4	2	6	557.4	0.938
5	4	4	6	401.3	0.922
6	4	6	6	343.8	0.868
7	4	2	8	842.4	0.907
8	4	4	8	692.6	0.892
9	4	6	8	579.6	0.841
10	4	2	10	1169.6	0.887
11	4	4	10	1067.5	0.816
12	4	6	10	994.4	0.815
13	4	2	12	1808.8	0.769
14	4	4	12	1535.7	0.751
15	4	6	12	1418.4	0.727

Table 3 Test samples For Bending Test (EVA)
(The outer plates and interlayer thickness changeable)

Test samples For Bending Test (EVA) IN				EVA	EVA
Sample No	outer glass thickness	interlayer No	Inner glass thickness	Max Force (N)	Max Disp (mm)
1	4	2	4	383.1	0.976
2	4	4	4	373.1	0.9759
3	4	6	4	345.0	0.9148
4	6	2	4	773.8	0.968
5	6	4	4	742.5	0.947
6	6	6	4	686.3	0.905
7	8	2	4	1264.0	0.939
8	8	4	4	1128.8	0.906
9	8	6	4	996.9	0.807
10	10	2	4	1681.3	0.912
11	10	4	4	1517.5	0.828
12	10	6	4	1342.5	0.743
13	12	2	4	2213.0	0.82
14	12	4	4	1761.9	0.714
15	12	6	4	1579.4	0.578

Table 4 Test samples For Bending Test (EVA)
(The inner plates and interlayer thickness changeable)

Test samples For Bending Test (EVA) OUT				EVA	EVA
Sample No	outer glass thickness	interlayer No	Inner glass thickness	Max Force (N)	Max Disp (mm)
1	4	2	4	386.8	1.021
2	4	4	4	368.4	0.969
3	4	6	4	361.4	0.948
4	4	2	6	791.3	0.934
5	4	4	6	766.5	0.908
6	4	6	6	674.4	0.878
7	4	2	8	1198.4	0.895
8	4	4	8	1054.4	0.858
9	4	6	8	990.6	0.803
10	4	2	10	1689.0	0.841
11	4	4	10	1504.0	0.792
12	4	6	10	1308.8	0.686
13	4	2	12	2175.0	0.825
14	4	4	12	1785.0	0.733
15	4	6	12	1524.0	0.573

Table 5 Test samples For Charpy Test (PVB)

Test samples For Charpy Test (PVB)				PVB
Sample No	outer glass thickness	interlayer No	Inner glass thickness	Absorbed Energy (J)
1	4	2	4	5.0
2	4	4	4	8.0
3	4	6	4	18.0
4	4	2	6	6.1
5	4	4	6	12.0
6	4	6	6	23.0
7	4	2	8	6.7
8	4	4	8	17.0
9	4	6	8	25.4
10	4	2	10	7.3
11	4	4	10	20.0
12	4	6	10	32.0
13	4	2	12	8.0
14	4	4	12	29.0
15	4	6	12	37.0

Table 6 Test samples For Charpy Test (EVA)

Test samples For Charpy Test (EVA)				PVB
Sample No	outer glass thickness	interlayer No	Inner glass thickness	Absorbed Energy (J)
1	4	2	4	3.1
2	4	4	4	6.5
3	4	6	4	11.2
4	4	2	6	3.4
5	4	4	6	7.1
6	4	6	6	12.7
7	4	2	8	4
8	4	4	8	8.3
9	4	6	8	15.1
10	4	2	10	4.3
11	4	4	10	10.6
12	4	6	10	16.7
13	4	2	12	4.6
14	4	4	12	12.1
15	4	6	12	18.5

APPENDIX B MINITAB REGRESSION ANALYSIS OUTPUT

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Welcome to Minitab, press F1 for help.
* NOTE * All values in column are identical.
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Regression Analysis: MAX FORCE IN PVB INTER LAYER versus X1, X2, X3

```
* X3 is (essentially) constant
* X3 has been removed from the equation.
```

The regression equation is

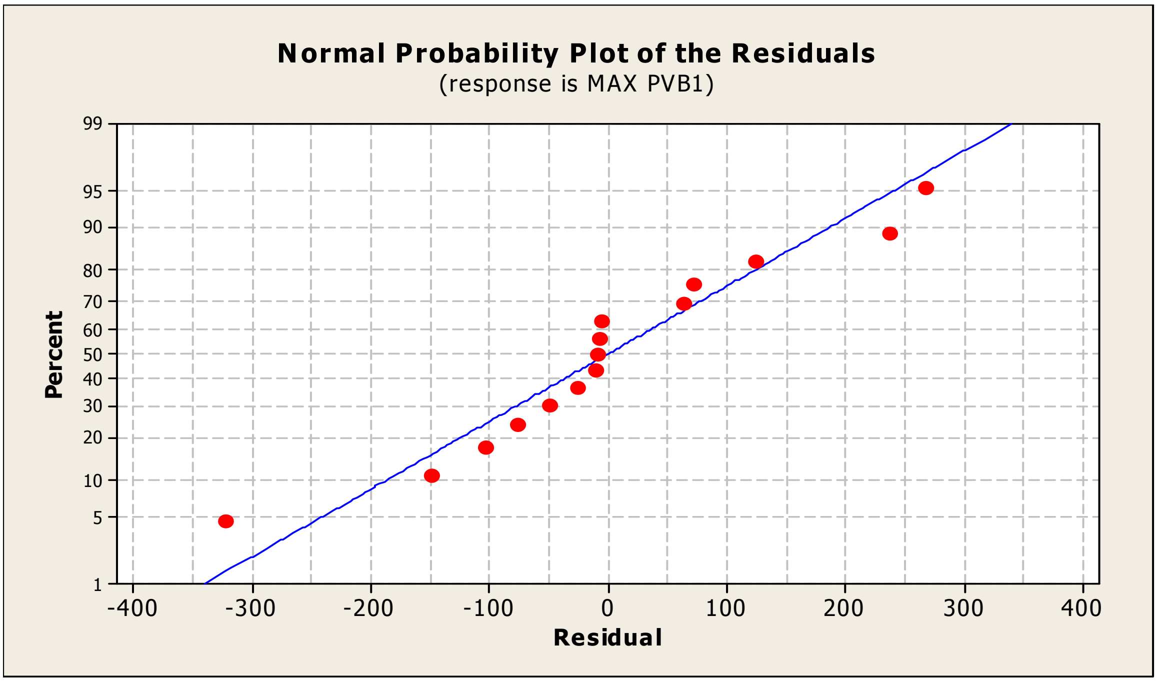
MAX PVB1 = - 348 + 174 X1 - 58.3 X2

Predictor	Coef	SE Coef	T	P
Constant	-347.9	157.4	-2.21	0.047
X1	173.88	14.37	12.10	0.000
X2	-58.29	24.89	-2.34	0.037

S = 157.443 **R-Sq = 92.7%** **R-Sq(adj) = 91.5%**

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	2	3763943	1881972	75.92	0.000
Residual Error	12	297460	24788		
Total	14	4061403			

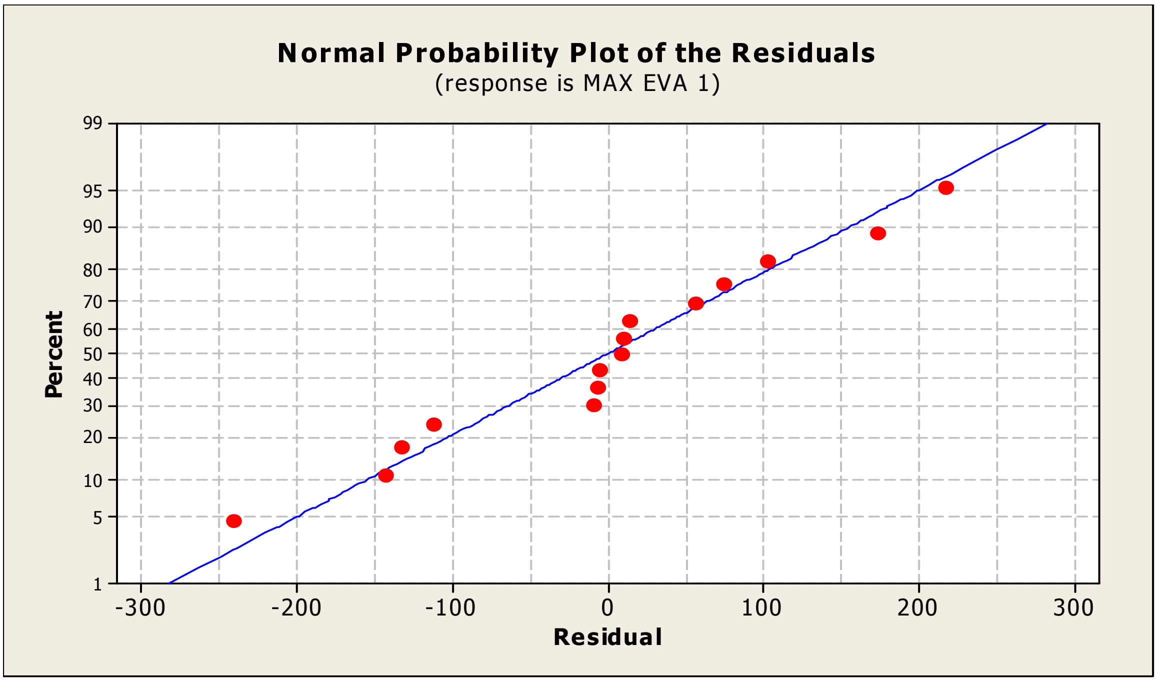


Norm. plot of Residuals for MAX FORCE IN PVB INTER LAYER

Results for: Worksheet 2

Regression Analysis: MAX FORCE IN EVA INTERLAYER versus X1, X2, X3

```
* X3 is (essentially) constant
* X3 has been removed from the equation.


The regression equation is
MAX EVA 1 = - 88 + 185 X1 - 68.3 X2


Predictor     Coef  SE Coef      T      P
Constant     -87.8    130.9  -0.67  0.515
X1          185.01    11.95  15.48  0.000
X2          -68.26    20.70  -3.30  0.006


S = 130.899   R-Sq = 95.4%   R-Sq(adj) = 94.7%


Analysis of Variance

Source          DF       SS       MS       F      P
Regression       2  4293644  2146822  125.29  0.000
Residual Error  12   205614    17134
Total           14  4499257
```



Norm. plot of Residuals for MAX FORCE IN EVA INTERLAYER

Results for: Worksheet 3

Regression Analysis: MAX ABSORBED ENERGY FOR PVB versus X1, X2, X3

```
* X1 is (essentially) constant
* X1 has been removed from the equation.


The regression equation is
```

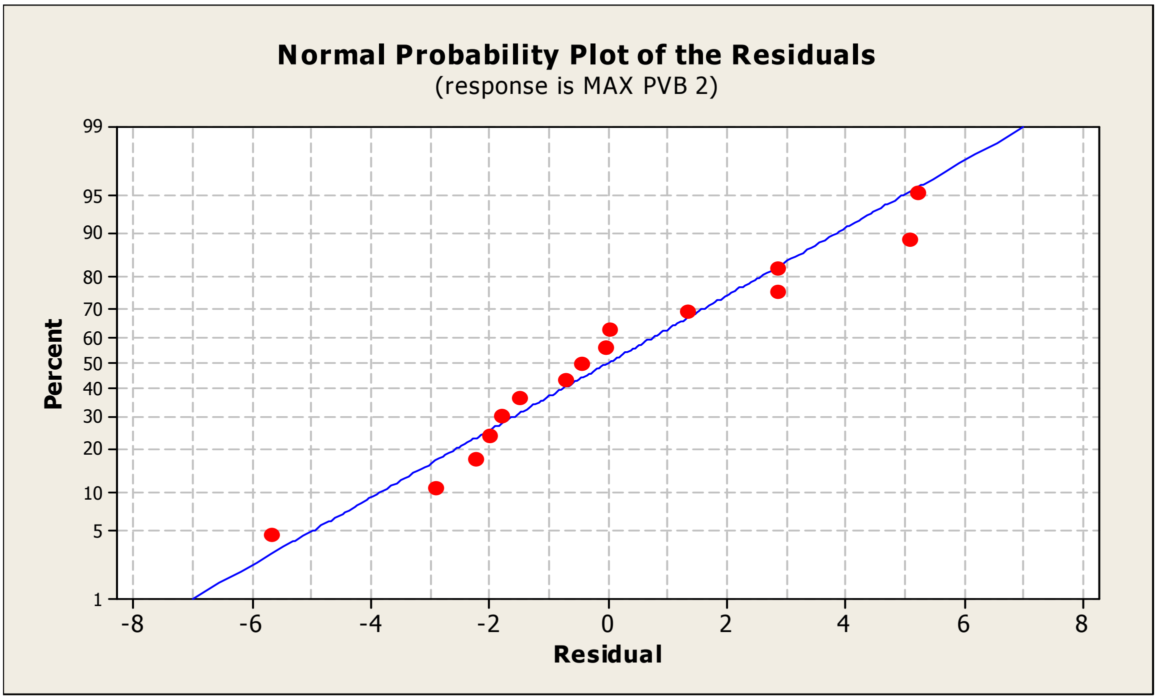
MAX PVB 2 = − 17.4 + 5.12 X2 + 1.74 X3

Predictor	Coef	SE Coef	T	P
Constant	-17.387	3.254	-5.34	0.000
X2	5.1150	0.5145	9.94	0.000
X3	1.7367	0.2971	5.85	0.000

S = 3.25427   **R-Sq = 91.7%   R-Sq(adj) = 90.3%**

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	2	1408.45	704.23	66.50	0.000
Residual Error	12	127.08	10.59		
Total	14	1535.53			

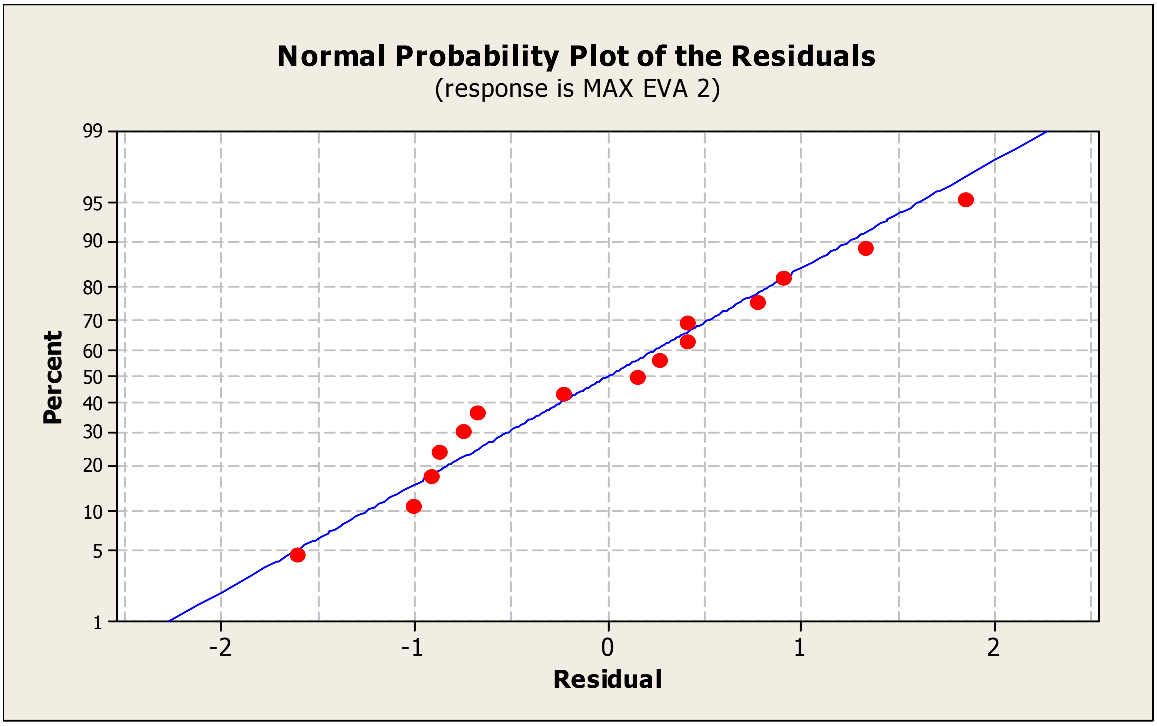


Norm.plot of Residuals for MAX ABSORBED ENERGY FOR PVB

Results for: Worksheet 4

Regression Analysis: MAX ABSORBED ENERGY FOR EVA versus X1, X2, X3

```
* X1 is (essentially) constant
* X1 has been removed from the equation.


The regression equation is
MAX EVA 2 = - 6.71 + 2.74 X2 + 0.620 X3


Predictor      Coef  SE Coef      T      P
Constant     -6.707    1.053  -6.37  0.000
X2           2.7400   0.1665  16.46  0.000
X3          0.62000  0.09612   6.45  0.000


S = 1.05299   R-Sq = 96.3%   R-Sq(adj) = 95.7%


Analysis of Variance

Source          DF      SS      MS       F      P
Regression       2  346.43  173.22  156.22  0.000
Residual Error  12   13.31    1.11
Total           14  359.74
```



Normplot of Residuals for MAX ABSORBED ENERGY FOR EVA

تأثير كل من سماكة الزجاج وسماكة طبقة الجلاتين على مقاومة الكسرو الثقب لزجاج الجلاتين

إعداد
عمر عبدالعزيز السعيد

المشرف
أ.د عصام جلهم

ملخص

الزجاج الجلاتين هو يتكون من لوحين من الزجاج أو أكثر بينهما مادة بلاستيكية عادة ما تكون(PVB) أو(EVA) حيث إنها بعد الكسر تبقي أجزاء الزجاج في مكانها ملتصقة بدون حدوث انتشار لها مما جعلها كثيرة الاستخدام في التطبيقات المعمارية وزجاج السيارات حيث أنها من أكثر المواد الزجاجية أماناً.

هذه الدراسة تشمل دراسة تأثير كل من (PVB) و(EVA) وعدد طبقات كل بالإضافة إلى سماكة الزجاج على مقاومة الكسر و مقدار الطاقة الممتصة عند الانكسار. بالإضافة إلى إيجاد معادلة رياضية تربط بين هذه المتغيرات وتفسر النتائج.

كل من النتائج و المعادلة المقترحة تبين أن تأثير زيادة عدد طبقات المادة البلاستيكية تقلل من مقاومة الكسر و تزيد من مقدرا الطاقة الممتصة.أما تأثير سماكة الزجاج فهو طردي مع مقاومة الانحناء و الطاقة الممتصة.